UNIVERSITY OF ALBERTA

BIOFILTRATION FOR ODOUR CONTROL IN LIVESTOCK FACILITIES

BY

AHMAD ARMEEN

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TO

MY WIFE, MAHVASH AND MY HANDSOME SONS MILAD, MAHYAR, AND MAHDIYAR, WHOSE PATIENCE AND SUPPORT HELPED, MAKE IT POSSIBLE.

ABSTRACT

Biofilters can be used to treat odours produced from animal facilities. However, their performance decreases with the presence of ammonia (NH_3) and hydrogen sulfide (H_2S) gases. The objective of this research was to determine the effect of NH_3 and H_2S on biofilter performance and design a biofilter system to treat the NH_3 and H_2S compounds in the odourous exhaust air from animal facilities.

In the **first experiment**, a combined bioscrubber and biofilter (with sulfuric acid and no acid) was designed with background NH_3 and H_2S concentrations of 21.4±5.2 and 3.0±1.6 ppmv, respectively. Elimination capacity (EC) and the removal efficiency (RE) of the bioscrubbers and EC, RE, and pH of the biofilters were significantly different ($p<0.05$). The concentrations of NH_3 and H_2S contributed to the variation in pH of biofilter leachate. With a 10s empty bed retention time (EBRT), odour concentrations were reduced by 66% and the concentrations of NH_3 and H_2S were reduced by 100 and 75%, respectively.

In the **second experiment**, a combination of one bioscrubber and four biofilters was designed. This system operated with 2, 20, 45, and 90 ppmv NH_3 injected into the biofilters. The ammonia concentrations significantly affected the EC, RE, and pH of the biofilters ($p<0.05$). No nitrate was produced in the biofilter with 90 ppmv NH_3 and the nitrate production in the biofilter with 45 ppmv NH_3 was negligible. There were no significant differences ($p>0.05$) in the total amount of nitrite and nitrate produced in the biofilters that were operated with 20, 45, and 90 ppmv ammonia concentrations. The ECs of the biofilters for ammonia nitrogen with the above concentrations of ammonia were 11.6±2.6, 111±5.6, 183±10.9 and 242±21.8 $g/m^3/d$. Meanwhile, the overall total nitrite and nitrate nitrogen were 8.6±1.5, 42.1±3.9, 40.8±4 and 31.9±5 $g/m^3/d$, respectively. The daily accumulation of NH_3-N + NH_4^+-N in the biofilters were 3.4±2.9, 70.6±5.9, 143.4±10.5, and 211.6±21.5 $g/m^3/d$, respectively. Olfactometry tests indicated that the odour concentration was reduced 50% by bioscrubber and 72% by combination of bioscrubber and biofilter with no NH_3 injection.

Nitrogen mass balance data were used to develop a prediction model. The outcome of this model predicted the amount of water, media volume, and EBRT based on NH_3, H_2S, airflow, and temperature input.

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1. INTRODUCTION

1.1 Biofiltration for Odour Control

Odours generated from intensive livestock production such as swine facilities in North America have become a major concern. The concern comes not only from a nuisance based air pollution and odour problem, but also from a health perspective, as some of these compounds may be toxic and have negative effects on humans (workers and neighbouring population), animals, and environment. For example, ammonia at the levels of 50 and 75 ppm has been shown to reduce the ability of young pigs to clear bacteria rom their lungs (Le et al., 2005; Drummond et al., 1978). However, increased pressure from the public and the potential impact on the environment have prompted the need to find a method to quantitatively control the odours and bioaerosols in the environment surrounding agricultural facilities, notably pig farms.

Fundamental types of air pollution control can be categorized as chemical methods, biological methods (Biofilter, Biotrickling filter, and Bioscrubber), or a combination of the two. Several forms of treatment units have been developed such as condensation, adsorption, absorption, thermal and catalytic incineration, and ozone treatment (Devinny et al., 1999; O' Neil et al., 1992).

Biofiltration is a relatively modern pollution control technology that utilizes microorganisms to oxidize volatile organic compounds (VOCs) and oxidizable inorganic gases in contaminated air. The end products of biodegradation of air pollutants are carbon dioxide, water, and microbial biomass. Two basic removal mechanisms occur simultaneously during the biofiltration process: absorption/adsorption and bio-oxidation. With enough residence time, air contaminants will diffuse into the biofilm and on to the filter medium, where they are biodegraded (Devinny et al., 1999; Ottengraf, 1986).

The use of biofiltration for controlling odours has become increasingly widespread, especially in Europe, Japan, and now in North America as well (Devinny et al., 1999; Wittorf et al., 1993; Leson et al., 1991; Bohn, 1990; Ottengraf and Diks, 1990; Scholtens and Demmers, 1990; Ottengraf, 1987). For treating moderate gas flows containing low concentrations of odourous compounds, biofilters have been shown to have the greatest potential for cost-effective operation. They have been used successfully in a wide variety of settings for removal of odour and toxins and to control emissions from wastewater

treatment, chemical and pharmaceutical manufacturing, livestock production, composting operations, food processing, oil and gas, and petrochemical facilities (Devinny et al., 1999; Coleman et al., 1995; Dawson, 1993; Leson and Winer, 1991; Van Eyk and Vreeken, 1991; Werner et al., 1986). Moreover, recent research indicates an interest in the area of biofiltration for odour control and airborne nutrient removal for livestock facilitiy emissions (Liberty and Taraba, 1999; Nicolai and Janni, 1999; von Bernuth et al., 1999; Zhang et al., 1999; Nicolai and Janni, 1997; Li et al., 1996).

Many research projects have been conducted in the areas of biofiltration from different perspectives. To date, most have concentrated on control of operating parameters (short term), medium choice, retention time, and on a few odourous compounds such as hydrogen sulphide, ethanol, and ammonia. Little research has been reported on chemical accumulation and by-products in the biofilter media. There is a lack of information about by-products of biofiltration such as nitrite, nitrate, sulphate, and availability of toxic materials, notably ammonia and ammonium in the biofilter media when operated in hog barns (short- and long-term operations). Furthermore, there is insufficient information about water application for controlling the toxicity of by-products. In order to have stable biofiltration in swine facilities, it would be necessary to know, in a quantitative sense, what type of materials predominantly enter the biofilter, and what type of by-products are dominantly produced and accumulated in the biofilter. Moreover, assessment of both quantitative and qualitative effectiveness of biofilters needs to include the measurement of odour concentrations and hedonic tone through olfactometry.

This research, which focuses on these mentioned significant factors in the biofiltration process, will be organized using the following outline. Chapters one and two serve as an introduction to biofiltration, along with odour production, odour measurements (olfactometry), literature review, and parameters that affect the biofiltration operation. A mathematical model, (Appendix –A), is also introduced in chapter two. It predicts the operation outcome of a biofilter based on criteria reported in the literature. Chapter three outlines the objectives, and in the fourth chapter, the focus shifts toward the preliminary experiment with different media. Chapter five focuses on combination of bioscrubber and biofilter and the effect of dilute sulphuric acid on that

system when operated in a manure treatment plant with high concentration of hydrogen sulfide (H_2S) and ammonia (NH_3). Mass balance and by-products of ammonia injection are then discussed, followed by an analysis of water application methods for by-product control in chapters six and seven. Finally, in chapter eight, the revised predictive model for biofilter design and operation based on preceding facts and results will be described.

1.2 Odour Production in Livestock Facilities

Odourous compounds are predominantly the result of anaerobic (absence of oxygen) biodegradation. Anaerobic processes can be divided into three stages, namely hydrolytic, acidogenic, and methanogenic. There is no balance among the three stages. The acidogenic stage usually dominates. Products during this stage are odourous, and there is the potential for odour production around sites such as animal production facilities, manure storages, lagoons, composting facilities and treatment plants. Odour emissions from animal facilities vary by species, types of housing, manure storage and handling methods, and the size of odour sources.

After excretion, pig manure typically drops through a slatted floor of the swine building into drain gutters and, in some systems, remains there seven to 14 days before being discharged to an earthen manure storage. Swine manure slurries typically contain more than 95% MC (Midwest Plan Service, 1983). The physical properties and elemental composition of swine manure slurry and sludge stored in earthen manure storage are shown in Table 1.1. The volume of solids or sludge can be calculated as 5% of the total volume of manure present in the earthen manure storage. The organic content (C+N+H) of the slurry phase is approximately 50% of the dry weight of slurry, and the inorganic compounds listed in Table 1.1 account for about 15% (Zahn et al., 1997).

Table 1.1 Physical properties and elemental composition of slurry and sludge sampled from the swine waste storage basin (adapted from Zahn et al. 1997)

Parameter	Slurry	Sludge	Slurry/Sludge Ratio
pH	7.2±0.1	7.2±0.1	1
Solid content, mg mL^{-1}	21.9±3.3	31.3±1.7	0.70
% C, % of dry mass	37.2±0.4	42.3±0.2	0.88
% H, % of dry mass	5.2±0.2	6.2±0.1	0.84
% N, % of dry mass	3.0±0.1	2.3±0.2	1.30
Ca, mg L^{-1}	280±28	626±51	0.45
Cu, mg L^{-1}	14±4	50±8	0.28
Fe, mg L^{-1}	13±6	51±11	0.25
K, mg L^{-1}	1931±25	1675±14	1.15
Mg, mg L^{-1}	99±8	223±16	0.44
Na, mg L^{-1}	245±31	229±19	1.07
P, mg L^{-1}	612±20	980±36	0.62
S, mg L^{-1}	104±5	158±12	0.66
Zn, mg L^{-1}	7±1	41±9	0.17

Biological processes rely on many factors such as temperature, pH, and availability of proper nutrients. Another important factor is oxygen. Aerobic organisms require oxygen in order to survive. Aerobic biological processes can be presented by equation 1-1.

$$\text{Organic Matter (C, H, O, N, S)} + O_2 + \text{Aerobic bacteria} \longrightarrow CO_2 + H_2O + NH_3 + \text{Products } (NO_3^- + SO_4^{2-} \ldots) + \text{Energy} \quad (1\text{-}1)$$

Anaerobic organisms can be active in the absence of oxygen. The overall biochemical process for anaerobic systems can be written by equation 1-2.

Organic Matter (C, H, O, N, S) + Anaerobic bacteria $\longrightarrow$ $CO_2 + H_2O + NH_3 + H_2S +$ CH_4 + Products + Energy (1-2)

Volatile solids in a manure sample are removed when it is heated to 550±50 °C (Metcalf and Eddy, 1993). Organic materials having a boiling point ≤100°C and/or a vapor pressure >1mm Hg at 25°C are generally defined as volatile organic compounds (Metcalf and Eddy, 1993). These compounds have a low molecular weight, specific gravity, and water solubility (Wang et al. 1996). Generally, odours generated from feed and the animal body are not offensive, but those generated from manure and its decomposition during collection, storage, handling, and spreading are considered offensive. O'Neill and Philips (1992) reported that the total number of such odourous compounds which have been identified is 168, of which 30 have odour detection thresholds lower than or equal to 0.001mg/m^3. Six of the 10 compounds with the lowest odour detection thresholds all contain sulphur. Moreover, Schiffman et al. (2001) reported that a total of 331 different VOCs and VIOCs from swine facilities in North Carolina were identified by gas chromatography and mass spectrometry (GC/MS). The compounds identified included many acids, alcohols, aldehydes, amides, amines, aromatics, esters, ethers, halogenated hydrocarbons, hydrocarbons, ketones, nitriles, other nitrogen-containing compounds, phenols, sulfur-containing compounds, steroids, and other compounds.

Volatile fatty acids (VFAs) include formic acid (C_1), acetic acid (C_2), propionic and lactic acid (C_3), isobutyric and n-butyric acids (C_4), isovaleric and n-valeric acids (C_5), isocaproic and n-caproic acids (C_6), and n-heptanoic acid (C_7). VFAs, especially acetic acid are a source of odours during composting or anaerobic processes. VFAs form during bacterial decomposition of complex organic compounds through anaerobic processes. VFAs are unstable compounds and are converted to carbon dioxide and water under aerobic conditions, but through anaerobic degradation, they produce carbon dioxide and methane (Hobbs et al., 1997). The huge majority of these compounds are present in hog barns at concentrations below detection threshold and irritation thresholds, however, quantitative information on concentrations found in hog barns available for only 23 of the above gases (Table 1.2).

Table1.2 Quantitative gas emissions from a pig barn in former West Germany (Hartung, 1988)

Fatty acids: Trace Gas	Concentration in air (mg/m^3)
Acetic acid	0.189
Propionic acid	0.156
n-butyric acid	0.318
i-butyric acid	0.040
n- valeric acid	0.035
n-hexanoic acid	0.010
i- hexanoic acid	0.004
Heptanoic acid	0.003
Octanoic acid	0.005
Pelargonic acid	0.004
Phenols and indols:	
Phenol	0.023
p-cresol	0.039
Indole	0.001
Skatole	0.001
Methylamines:	
Dimethylamine	2.00
Trimethylamine	2.20
Other gases:	
Acetone	0.33
Ammonia	8.50
Hydrogen sulphide	2.00
Methane	0.004
Total	15.90

Quantitatively the most prevalent of odourous materials reported in Table 1-2 are ammonia (53%), hydrogen sulfide (12%), trimethylamine (14%), dimethylamine (12%), fatty acids (5%), phenols and indoles (0.4%).

Some aerobic and facultative bacteria can use nitrate and sulfate as electron acceptors and reduce them to nitrogen gas (N_2) and elemental sulfur (S). A microbial community will preferentially transfer electrons from an organic substrate to the most oxidizing electron acceptor available in the environment. Substances differ in their tendencies to accept electrons and become reduced or to donate electrons and become oxidized. This tendency is expressed as the redox potential of the substance (Brock and

Madigan, 1991). Redox potential (E_h) is an indicator of aerobic and anaerobic microbial utilization of potential electron acceptors. Redox potential of the NO_3^- (+300 to +600 mV) is much higher than that of most odour causing volatile fatty acids. Due to the low redox potential, odourous compounds cannot be generated in the existence of free oxygen (+600 mV) in aerobic digestion, but they may be present initially in manure (Atlas and Bartha, 1993).

Anaerobic degradation is the process by which organic matter is fermented by bacteria in the absence of free oxygen. The overall anaerobic process can be divided into three stages including hydrolysis, acidogenesis, and methanogenesis. The hydrolysis in the process involves the enzyme-mediated transformation of organic substrates such as lipids, polysaccharides, proteins, and nucleic acids to form fatty acids, monosaccharodes, amino acids, and purines and pyrimidines, respectively. The acidogenesis stage involves the bacterial conversion of the compounds resulting from the first step into methanogenic substrates such as H_2, CO_2, formate, methanol, methylamines, and acetate. The methanogenesis stage involves the bacterial conversion of the intermediate compounds into simpler end products, principally methane and carbon dioxide. Moreover, methanogenesis is the terminal step in the anaerobic digestion process, and methane escapes from the system, allowing the digestion process to proceed to completion. A specific group of bacteria known as methanogens is responsible for this terminal step. These bacteria are anaerobes that derive their energy requirements during the production of methane.

Organic polymers in swine feed are mostly hydrolyzed and absorbed by the intestine of the animal. Thus the acidogenic phase and the methanogenic phase could predominate in manure storage (Metcalf and Eddy, 1991). Figure 1.1 shows the overall pathway of anaerobic processes by which complex organic materials break down to the other simple molecules and by-products.

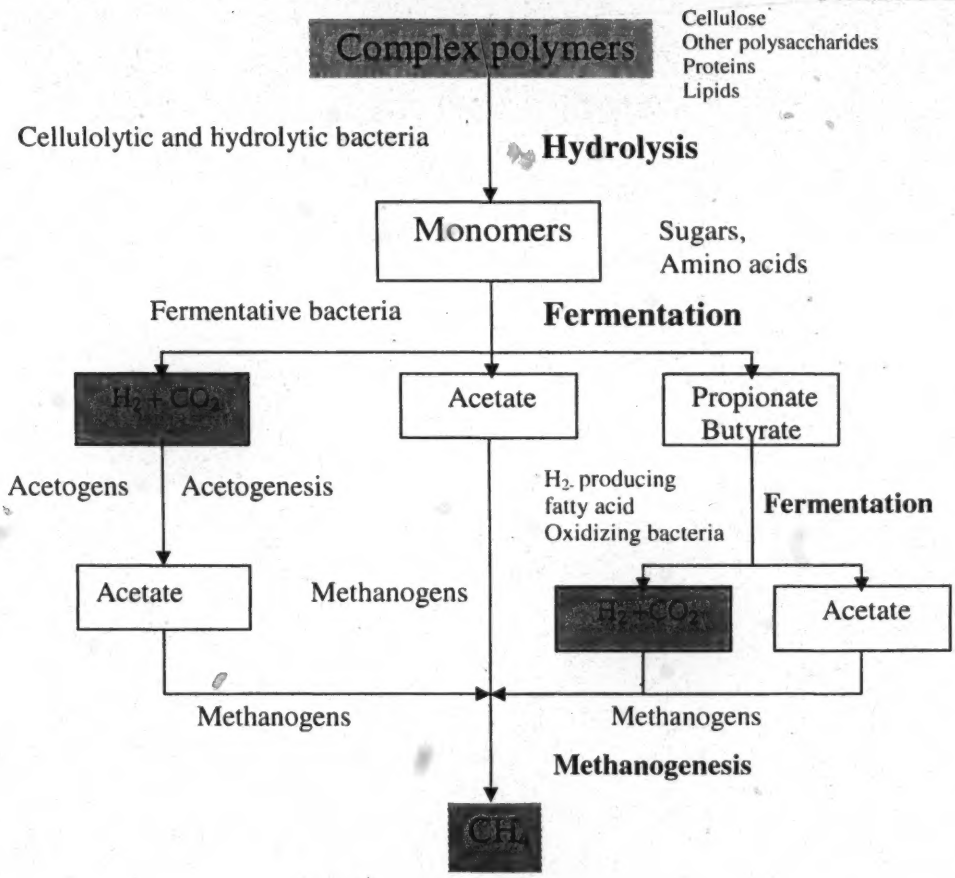


Figure 1.1 Schematic diagram of methane and methanogenesis process (adapted from Brock and Madigan, 1991)

The operation of anaerobic digesters requires close control of several parameters, such as temperature, retention time, pH, influent solids concentration, organic loading rates, toxic substances, nutrients, C:N, and C:P ratios.

Acid-forming bacteria are quite hardy and resistant to various inhibitors and changes in their environment and are not considered to be the rate or process-limiting factor in digestion. Methanogens, on the other hand, are slow growing and are strictly anaerobic and extremely sensitive to changes in their environment such as pH changes, presence of heavy metals, detergents, ammonia, sulfides, change in alkalinity, and temperature. In earthen manure storage pits, most molecules of celluloses and polymers

have been broken down into smaller molecules, and a limiting factor in the degradation of swine manure may be methanogens.

In general, the final products of microbial degradation of carbonaceous material in an anaerobic natural ecosystem are CH_4 and CO_2. In stored swine manure, little methane is formed. The rate of methanogenesis under storage conditions is not high enough to prevent the accumulation of products of acid forming fermentation. In other words, the acidogenic phase and the methanogenic phase in the microbial degradation of the complex substrates in swine manure may not be in balance. The imbalance between the process of acid formation (the acidogenic process) and methane production (methanogenic process) is the main key to understanding the accumulation of volatile compounds (malodourous products) in the degradation of swine manure. What actually causes the low rate of methanogenesis in stored swine manure is not clear, but when comparing the environment and operating conditions of manure storage and a digester under normal operation, we can say many factors such as temperature, pH, high concentration of organic materials, toxicity of by-products, and availability of toxic materials cause the low rate of methanogenesis in the manure storage.

1.3 Major Indicator of Odours

The major indicators for malodour from swine manure have been a topic of interest for many years. Merkel et al. (1969) reported that alcohols were not important in determining the nature of swine confinement manure odours. Barth and Polkowski (1974) found that the volatile organic acids correlated best with the odour intensity. Ammonia was thought to be useful as an indicator for malodour, but despite relatively high concentrations and easy determination it was proved to be a poor factor in evaluating odour intensities (Lunn and van De Vyver, 1977).

The major indicators of odourous materials include: volatile fatty acids (VFAs), sulfur containing volatile compounds, amine gases, aldehydes, and hydrocarbons.

1 - Volatile fatty acids (VFAs) are the most dominant odourous materials in swine manure. Total amounts of these contaminants in slurry range from 4 to 25 g/L. Acetic acid and propionic acid represent about 60 and 25%, respectively, of the total amount of volatile fatty acids (Miller and Varel 2003; Spoelstra, 1980). On the other hand, Hjn

artung (1988) reported that the concentrations of acetic acid, propionic acid and n-butyric acid in the air of swine barn were 0.19, 0.16, and 0.32 mg/m^3, respectively.

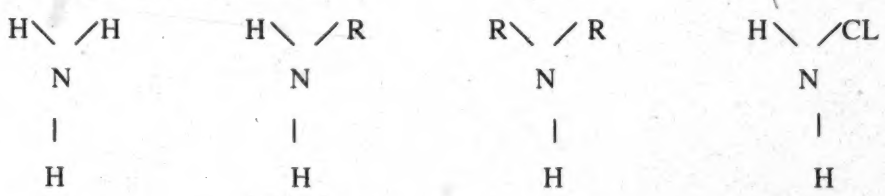
2 - Sulfur containing volatile compounds

The sulfide family include:

Hydrogen Sulfide Mercaptan Dimethyl Sulfide Dimethyl Disulfide

Hydrogen sulfide and methyl mercaptan are frequently reported as the primary constituents of swine manure odours and are, quantitatively, the most important sulfur containing odour compounds.

3- The amine family include:



Ammonia Methyl Amine Dimethyl Amine Chloro-Amine

The amines are contaminants, which can be produced from degradation of protein containing compounds under anaerobic conditions. The principal volatile amines include: methyl-, ethyl-, propyl-, butyl-, amyl-, iso-butyl-, iso-amyl, hexyl-, dipropyl-, and dibutyl-amine.

1.4 References

Atlas, R. M. and Bartha, R. 1993. Microbial Ecology: Fundamentals and Applications (3rd edition). The Benjamin/Cummings Publishing Company, Inc. Redwood City, California, USA.

Barth, C.L., L.B. Polkowski. 1974. Identifying Odourous Components of Stored Dairy Manure. Tran. The ASAE. 17(4): 741-747.

Bohn, Hinrich L. 1990. Control of VOC emissions from waste management facilities. Comments. J. Environ. Eng. (N.Y.) 116:1002-1004.

Brock T. D. and Madigan, M. T. 1991. Biology of Microorganisms (Sixth Edition). Prentice-Hall, Inc. Englewood Cliffs, New Jersey 07632.

Coleman, R. N., Dombroski, E. C., and Milner, R. 1995. Development and optimization of a modular biofilter for use as a sulphide process emission abatement technology for industry. Final Report. Microbiology Research & Development Alberta Environmental Centre and Milner Engineering, Vegreville, Alberta. (#23440-4-1025/01-SQ: DSS File #028SQ-23440-4-1025).

Dawson, D.S. 1993. Biological Treatment of Gaseous Emissions. Water Environment Research, Vol. 65, No. 6, p 368-371.52 ref.

Devinny, J. S., Deshusses, M.A., and Webster, T. S. 1999. Biofilteration for air pollution control. Lewis Publishers, New York, USA.

Drummond, J G., Curtis, S. E., and Simon, J. February, 1978. Effects of atmospheric ammonia on pulmonary bacterial clearance in the young pig. Am J Vet Res, 39 (2), 211-212.

Hartung, J., 1988. Tentative calculations of gaseous emissions from pig houses by way of the exhaust air. In: Nielsen,V. C., Vooburg J., L' Hermite, P. (eds). Volatile emissions from livestock farming and sewage operations. London: Elsevier Applied Science, 54-58.

Hobbs, P. J., T. H. Misselbrook, and B. F. Pain. 1997. Characterisation of odorous compounds and emissions from slurries produced from weaner pigs fed dry feed and liquid diets. North Wyke, Okehampton, Devon, EX20 2SB, UK. J Sci Food Agric. 73: 437-445

Le, P.D., A.J.A. Aarnink, N.W.M. Ogink, P.M. Becker, M.W.A. Verstegen, 2005. Odour from animal production facilities: its relationship to diet. Nutrition-Research-Reviews. Wallingford, UK: CAB International 18(1):3-30.

Leson, G., J. Rickun, and M. Henson. 1991. Biofiltration-An Innovative Control Technology for Odors and Air Toxics. 1991 Environmental Conference – TAPPI Proceedings pp. 349-354.

Leson, G. and A. M. Winer. 1991. Biofiltration: an innovative air pollution control technology for VOC emissions. Journal of Air Waste Management Association, 41(8), 1045-1054.

Li, X. W., S. J. Hoff, D. S. Bundy, J. Harmon, H. Xin, and J. Zhu. 1996. Biofilter – A malodour control technology for livestock industry. J. Environ. Sci. Health 31 (9): 2275-2285.

Liberty, K. R., and J. L. Taraba. 1999. Solid-state biofilter for nitrification. ASAE Paper No. 99-4030. St Joseph, Mich.: ASAE.

Lunn, F., and J. van De Vyver. 1977. Sampling and Analysis of Air in Pig Houses. Agriculture and Environment. 3: 159-169.

Miller, D.N., and Varel, V.H., 2003. Swine manure composition affects the biochemical origins, composition, and accumulation of odourous compounds. Journal of Animal Science. 81(9): 2131-2138.

Midwest Plan Service, Iowa State University, 1983. Swine housing and equipment handbook. Fourth edition. Ames IA 50011-3080. PP. 249-253.

Merkel, J. A., 1981. Managing Livestock Wastes. AVI, Inc. Westport. USA.

Merkel, J.A., Hazen, T.E., and Miner, J.R. 1969. Identification of Gases in a Swine Confinement Building Atmosphere. Trans. The ASAE. 12: 310-316.

Metcalf and Eddy, Inc. 1991. Wastewater engineering: Treatment, disposal, and reuse (3rd edition). McGraw-Hill, Inc. New York. NY.

Metcalf and Eddy, Inc.1993. Wastewater engineering: Treatment, and reuse. (4rd Edition). Revised by: G. Tchobanoglous, F.L. Burton, and H.D. Stensel, McGraw-Hill, Inc. New York. NY.

Nicolai, R. E., and K. A. Janni. 1997. Development of a low cost biofilter for swine production facilities. ASAE Paper No. 97-4040. St. Joseph, Mich.: ASAE.

Nicolai, R. E., and K. A. Janni. 1999. Effect of biofilter retention time on emissions from dairy, swine, and poultry buildings. ASAE Paper No. 99-4149. St. Joseph, Mich.: ASAE.

O'Neill, D. H., and V. R. Phillips, 1992. Review of the control of odour nuisance from livestock buildings: Part 3: Properties of the odourous substances which have been identified in livestock wastes or in the air around them. J. Agri. Engng Res. 53: 23-50.

Ottengraf, S.p.p. 1987. Biological systems for waste-gas elimination using scrubber, trickling filter or biofilter systems; xenobiotic degradation. Trends in Biotechnology 5 (5): 132-136.

Ottengraf, S.P.P., J. J. P. Meesters, A. H. C. van den Oever, and H. R. Rozema. 1986. Biological elimination of volatile xenobiotic compounds in biofilters for waste-gas waste-disposal, deodorization by filtration. Bioprocess Engineering 1 (2): 61-69.

Ottengraf, S.P.P., and R. Diks. 1990. Biological purification of waste-gases waste-gas treatment, deodourization and air purification using e. g. biofilter, scrubber and trickling filter. Chimicaoggi 8 (5): 41-45.

Schiffman, S. S., J. L. Bnnett, J. H. 2001. Quantification of odors and odorants from swine operations in North Carolina. Agricultural and Forest Meteorology. 108: 213-240.

Scholtens, R., T.G.M. Demmers. 1990. Biofilters and air scrubbers in the Netherlands. Odour Ammonia Emissions from Livestock Farming Proc. Semin. Nielsen, V.C. (Ed), Voorburg, J.H. (Ed), and L'Hermite, Pierre (Ed). Silsoe, United Kingdom, 26 March. London: Elsevier London, UK. pp. 92-96.

Spoelstra, S.F. 1980. Origin of Objectionable Odourous Components in piggy Wastes and ThePossibility of Applying Indicator Components for Studying odour development. Agriculture and Environment. 5: 241-260.

van Eyk, J., and C. Vreeken. 1991. In situ and on-site subsoil and aquifer restoration at a retail gasoline station. (conference paper). In: In Situ Bioreclamation. R.E. Hinchee and R.F. Olfenbuttel (eds). Butterworth-Heinemann. Boston, MA. pp, 303-320.

Von Bernuth, R. D., K. Vallieu, and H. Nix. 1999. Experiences with a biofilter on a slatted floor hog barn. ASAE. Paper No. 99-4148. St. Joseph, Mich: ASAE.

Wang, W., J. L. Schnoor, and J. Doi. 1996. Volatile organic compounds in the environment. ASTM special technical publication 1261. West Conshhocken PA.

Werner, W., H. G. Liebe, and B. Striefler. 1986. Emission Control with Biofilters: Application, Design and Operational Experience. Seventh World Clean Air Congress, 537-544. Sydney, Australia, 25 August 1986.

Wittorf, F., J. Klein, K. Koerner, O. Unterlohner, and H. Ziehr. 1993. Biocatalytic treatment of waste air. Chemical Engineering and Technology (Germany) 16: 1: 40-45

Zahn, J. A., J. L. Hatfield, Y. S. Do, A. A. Dispirito, D. A. Laird, and R. L. Pfeiffer, 1997. Characterization of volatile organic emissions and wastes from a swine production facility. J. Environ. Qual. 26: 1687-1696.

Zhang, Z., T. L. Richards, and D. S. Bundy. 1999. Effect of organic cover biofilters on odors from liquid manure storage. ASAE Paper No.99-4087. St. Joseph, Mich.: ASAE.

2. MEASUREMENT AND TREATMENT OF ODOUR

2.1 Odour Characteristics and Measurement

Of the five senses (taste, touch, hearing, sight, and smell), the sense of smell is the most complex and unique in structure and organization (McGinley et al., 2000). Odours are sensations caused by the reception of a stimulus by the olfactory sensory system, which includes two separate subsystems: the olfactory epithelium and the trigeminal nerve (ASCE, 1995). By breathing normally, only 10% of inhaled air passes up and under the olfactory receptors, located at the back of the nasal cavity. When sniffing takes place, however, whether a voluntary or involuntary sniff reflex, more than 20% of inhaled air is carried to the olfactory receptors because of turbulent action in front of the turbinates (McGinley et al., 2000). The human nose contains approximately one million odour receptor cells (Moulton, 1974). There are hair-like cilia that extend through the mucous layer at each end of each olfactory receptor. Experimental evidence shows that the cilia of the nerve cells are the actual receptors of the odour stimulus (Gesteland, 1983). Odourous compounds can be tasted when an odourant, which is a substance that activates the sense of smell, is absorbed by the mucous membrane in the mouth and throat. The molecular attributes along with chemical and physical structures of most odourous substances create the stimuli to the olfactory sensory cells that are responsible for smell (ASCE, 1995). The important parameters or odour terminology that will assist understanding odours and interpreting odour evaluation data include:

a) Odour concentration

b) Odour intensity

c) Odour persistence

d) Odour character, and

e) Hedonic tone

The most important odour parameter is odour concentration. Odour intensity, odour persistence, hedonic tone and odour character are generally applied to the food, beverage, perfume, and cosmetics industry. The odour concentration parameter, however, is applied to all areas related to odour, flavour, and smelling. More details and information about odour measurement are published by Feddes et al., (2001); McGinley et al., (1999, 2000).

2.1.1 Odour Concentration

Dilution of an odour is the physical process that occurs naturally in the atmosphere down wind of an odour-generating source. The "receptor" (citizen in the community) sniffs the diluted odour. The dilution ratio is an estimate of the number of dilutions needed to make the odour "non-detectable (threshold). If the receptor detects the odour, then the odour in the atmosphere is above the threshold level (suprathreshold).

The odourant concentration can be measured by determining the mass concentration of pure odourous substances or by determining the dilution factor of mixtures of odourants required to reach the detection threshold (ASTM E – 758, 1991). The technique used to measure odour concentration by dilution to threshold is called olfactometry. In this method, the human nose is used as the sensor of odours. The olfactory organ in the human nose is capable of detecting and discriminating between many thousands of different odours and can detect some of them in concentrations lower than those detectable by currently available analytical instruments, such as a gas chromatograph (ASCE, 1995). Table 2.1 shows the detection threshold and recognition threshold of odourous gases that potentially can be emitted from manure. This table shows that the detection threshold of some of the odourous compounds, such as hydrogen sulfide, is as low as 0.5 ppb. Therefore, a human panel is essential for determining the odour concentrations.

Table 2.1 Components of manure odours (modified from Hamilton, 2003; ASCE, 1995; Zhu et al., 1997; Schiffman et al., 2001)

Manure Odourous compounds	DT* (ppb)	RT** (ppb)	Odour Description
Organic Acids:			
Acetic Acid CH_3COOH	145	1,000	Vinegar
Propionic Acid C_2H_5COOH	36	300	
Butyric Acid $CH_3(CH_2)CHCOOH$	1	1.1	Sour Meat
Iso-Valeric Acid $(CH_3)C_2H_3COOH$	1.2	20	
Valeric Acid C_4H_9COOH	-		
Alcohols, Aldehydes, Ketones:			
Methanol CH_3OH	-	100,000	Sweet
Formaldehyde HCHO	-	1,000	Straw, punget
Acetylaldehyde CH_3CHO	67	210	Fruity, pungent
Acetone CH_3COCH_3	-	100,000	Sweet, pugent
Methyl Ethyl Ketone $CH_3CH_2COCH_3$	-	10,000	Sweet
Phenolic compounds:			
Phenol •-OH	5.7	1,000	Medicinal
P-Cresol CH3-•-OH	8.0	-	
Nitrogen Compounds:			
Ammonia NH_3	17,000	37,000	Sharp, pungent
Methylamine CH_3NH_2	4700	-	Fishy, pungent
Dimethylamine $(CH_3)_2NH$	340	-	Fishy, pungent
Diethylamine $(C_2H_5)_2NH$	-	500	Fishy, pungent
Indole $C_6H_4(CH)_2NH$	1.0	-	Fecal
Skatole (C_9H_9N)	1	50	Fecal, pungent
Sulfur Compounds:			
Hydrogen Sulfide H_2S	0.5	4.7	Rotten Egg
Methyl Mercaptan CH_3SH	0.5	2.1	Rotten Cabbage
Dimethyl Sulfide $(CH_3)_2S$	1.1	1.1	Rotten Vegetable
Diethyl Sulfide $(C_2H_5)_2S$	6.0	6.0	Rotten Vegetable

* DT = Detection Threshold (minimum odourant concentration required to perceive the existence of the stimulus).

** RT = Recognition Threshold (minimum odourant concentration required to recognize the character of the stimulus).

2.1.2 Detectability or Threshold

Detectability, or threshold, refers to the minimum concentration of an odourant that produces an olfactory response or sensation (ASCE, 1995). An odour panel determines the detection threshold. An odour panel consists of a specified number of people. The

numerical result of olfactometry typically is expressed when 50% of the panel correctly detects the odour. At odour intensity levels at or barely above "threshold," odours are difficult to perceive. As a result, the actual values depend on the type of sensory test, panelist selection, detectability criterion, and other factors.

An odour detection threshold relates to the minimum odourant concentration required to perceive the existence of the stimulus, whereas an odour recognition threshold relates to the minimum odourant concentration required to recognize the character of the stimulus. Typically, the recognition threshold exceeds the detection threshold by a factor of 2 to 10 (Dravnieks and Jarke, 1980).

During an odour test, the odour panelist (assessor) sniffs a dilute sample of the odour as it is discharged from the olfactometer as one of three sample presentations (one presentation with the dilute odour and two with odour free air). The assessor sniffs all three of the presentations and must select the one of the three that is different from the other two, even if they must guess. This statistical approach is called "triangular forced-choice." The assessor declares to the test administrator if the selection is a "guess", a "detection" (the selection is different from the other two), or a "recognition" (the selection smells like something) as defined by ASTM E679-91. The assessor is then presented with the next set of three presentation choices, one of which contains the diluted odour sample. However, this next set of three samples presents the odour at a higher concentration (e.g. two times higher). The assessor continues to additional levels of higher concentration (lower dilution) presentations following the "triangular forced-choice" procedure and the required designation of "guess", "detect", or "recognition". This statistical approach of increasing levels of sample presentation is called "ascending concentration series."

Therefore, "odour concentration" or odour strength is a number derived from the laboratory dilution of sample odours. The dilution ratio (total presentation volume divided by odour sample volume) at each sample presentation level is used to calculate the concentration of the evaluated sample. Normally based on the European standard, the concentration of the odour samples is reported as odour unit per cubic meter (OU/m^3). The number of European odour units (OU_E) in $1m^3$ of neutral gas at standard conditions is the odour concentration of the sample. One OU_E is the amount of odourant evaporated

in 1 m^3 of neutral gas at standard conditions that elicits a physiological response from a panel (detection threshold) equivalent to that elicited by 1 European reference odour mass (EROM) evaporated in $1m^3$ of neutral gas at standard conditions. One EROM is equivalent to 123 µg of n-butanol. This amount of evaporated n-butanol in $1m^3$ of neutral gas produces a concentration of 0.040 µmol/mol (ppmv).

Table 2.2 is an example of an odour evaluation data sheet from an odour laboratory. As an example, follow the results of panelist 1 (A) in Table 2.2. This panelist did not indicate "detection" of the odour at dilution level 6, which is a dilution ratio of 500, but did indicate detection at the next highest odour concentration (lower dilution ratio) of 250 (two times more odourant than 500). The panelist's individual estimated detection threshold is the geometric mean between 500 and 250, or 353. The result of this statistical method is called the "best-estimate" threshold (McGinley et al., 1999).

(Log 500 + Log 250)/2 = (2.698+ 2.397)/2 = 2.548 and Anti Log 2.548 = 353 OU/m^3

The geometric mean is used when calculating the "best estimate" threshold due to the lack of "equal variance" along the dilution ratio scale (Stevens 1962).

The odour threshold of the sample with seven panelists (Table 2.2) can be calculated in the following way:

$$\text{Log of (DT)} = (\text{Log A} + \text{Log B} + \text{Log C} + \ldots)/N = Y \qquad (1\text{-}3)$$

$$\text{DT} = \text{Anti log (Y)} \quad \text{or} \quad \text{DT} = 10^{(Y)} \qquad (1\text{-}4)$$

Where:

A, B, C = the estimated detection thresholds of the panelists 1, 2, 3, respectively

N = number of panelists

Based on the example in Table 2.2 the DT of the sample can be estimated in the following:

Log of DT = (Log 354 + Log707 + Log 177 + Log 354+Log 354 + Log 177 + Log 177)/7 = 2.462

DT = Anti log of (2.462) = $10^{2.462}$ = 290 OU/m^3

Computers that give fast and more accurate results will do the above calculations.

Table 2.2 Odour testing data sheet for odour evaluation laboratory at the University of Alberta

Sample: bag2	Airflow: 10000 (cc/Min)												
	D-level	DL-03	DL-04	DL-05	DL-06	DL-07	DL-08	DL-09	DL-10	DL-11	DL-12		
	D-ratio	4000	2000	1000	500	250	125	63	32	16	8	IDT	
Position	Panelist												
1	A	?*	?*	G-	G+	D+	D+			?*	?*	354	
2	B	?*	?*	G+	D+	D+				?*	?*	707	
3	C	?*	?*	G+	G+	G+	D+	D+		?*	?*	177	
4	D	?*	?*	G-	G-	D+	D+			?*	?*	354	
5	E	?*	?*	G-	G-	D+	D+			?*	?*	354	
6	F	?*	?*	G-	G-	G+	D+	D+		?*	?*	177	
7	G	?*	?*	G-	G+	G-	D+	D+		?*	?*	177	
												290	OU/m^3

G^+ = Panelist pressed guess button when odour was present. G^- = Panelist pressed guess button when odour was not present. D^+ = panellist pressed detect button when odour was present. D^- = Panelist pressed detect button when odour was not present. IDT =Individual Detection threshold. ?* = diluted odour not presented.

2.1.3 Odour Emission Rate

Olfactometry can be used for estimating the odour emission rates of animal facilities such as barns and manure storage (lagoon, etc.). Basically polluted air with a measured odour concentration (overall average) comes from the sources in a certain period of time and, by estimating the ventilation rate, the odour emission rate can be calculated (ASCE, 1995). Equation 1-5 can be used for estimation of the odour emission rate of a barn.

$$OER_b = C_o \times V_b \qquad (1\text{-}5)$$

Where:

OER_b = the odour emission rate of the barn (OU/s)

C_o = the overall odour concentration of the barn (OU/m^3)

V_b = the ventilation rate of the barn (m^3/s)

Normally, a wind tunnel or vented hood is used in providing odour samples for estimating the odour concentration of manure storages (lagoons). Then, equation 1-6 is used for estimating the odour emission rate of the storage:

$$OER_m = \frac{C_o \times Q_s \times A_m}{A_s} \qquad (1\text{-}6)$$

OER_m = the emission rate of the manure storage facility in OU/s

C_o = the odour concentration in OU/m^3

Q_s = the air flow rate in m^3/s across a known manure surface area (air flow through the wind tunnel)

A_s = the known surface area in m^2 (surface under the wind tunnel) and

A_m = the surface of the manure storage m^2.

2.1.4 Odour Intensity

Odour intensity is a measure of the strength of the odour sensation. This is related to the odourant concentration, which is a different category of measurement. As an example of odour intensity measurement, Table 2.3 shows the five-levels of odour intensity based on n-butanol scaling. The intensity of an odour is perceived directly without any knowledge of the odourant concentration or of the degree of air dilution of the odourous sample needed to eliminate the odour.

Table 2.3 Odour intensity referencing scales (OIRS) n-butanol odour intensity (ppm) (adapted from McGinley, 2000)

Strength (Intensity) Categories	Nuisance	Odour Intensity Referencing Scale n-butanol (ppm) in water
0. No Odour		0
1. Very Faint / barely perceivable (DT)	An odour that could be detected by the experienced inspector.	25
2. Faint / Identifiable (RT)	An odour so weak that the average person might detect it.	75
3. Noticeable/ Easily Perceivable	An odour of moderate intensity that would be readily detected.	225
4. Strong	A very unpleasant odour that would force itself upon the attention of the average person.	675
5. Very strong /Repulsive	The air with high intensity of odour absolutely unfit to breath.	2025

The odour intensity of a sample (odorous/foul air) is represented in parts per million of n-butanol. A larger value of n-butanol indicates a stronger odour, but not in simple numerical proportion. Equations 1-7 and 1-8 describe the relationship between odour intensity (I) and concentration (C) (ASCE, 1995).

$$T\ I\ (perceived) = k(C)^n \qquad (1\text{-}7) \text{ or } \qquad \log I = \log k + n \log C \qquad (1\text{-}8)$$

Where k is a constant and n is the exponent:

This relationship between I and C is known as Stevens' law, or the power law (Dravnieks, 1979). Depending on the odourant, n varies from approximately 0.2 to 0.8. For an odourant with an n value equal to 0.2, a tenfold reduction in concentration reduces the perceived intensity by a factor of 1.6. However, for an odourant with an n value of 0.8, a tenfold reduction in concentration lowers the perceived intensity by a factor of 6.3. This is an important concept related to the problem of odour intensity reduction of a substance by air dilution or other means (ASCE, 1995). Figure 2.1 shows the relationship

between the odour intensity and the odour concentration. When the concentration of an odour increases the intensity will increase too.

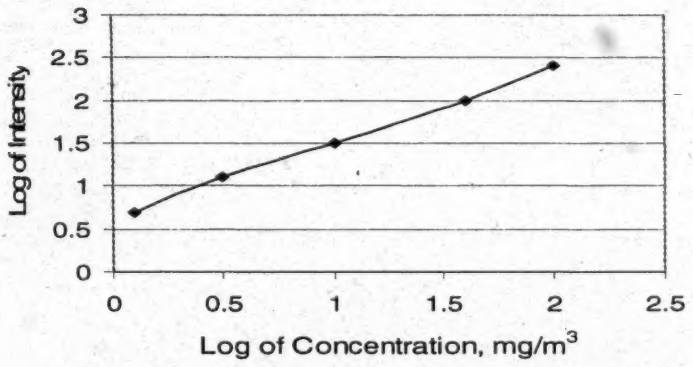


Figure 2.1 Log of odour intensity vs log of odour concentrations (power law) (adapted from McGinley et al., 2000)

Figure 2.2 shows a comparison of the persistency of odours A and B. The slope of each line illustrates the persistency of that odour. Odour 'A', with the flatter slope, represents a more persistent odour. In other words, odour 'A' would have a greater "hang time" in the ambient air (McGinley et al., 2000).

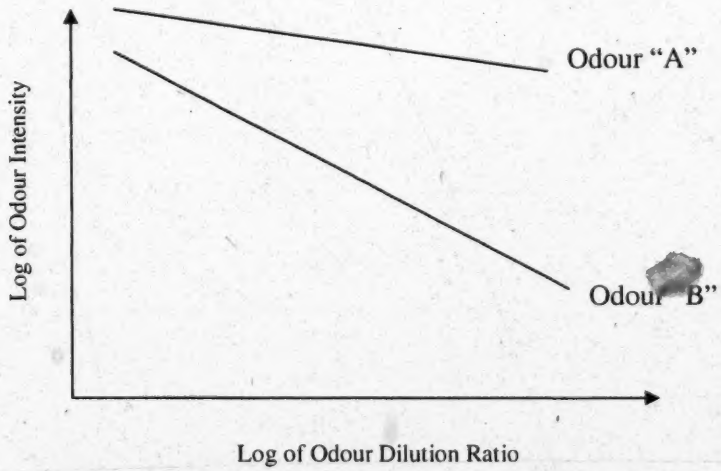


Figure 2.2 Comparison of odourants based on dose-response\

2.1.5 Odour Character

The term character is used to describe the smell of a particular odour. Odour character is

not dependent on concentration. As an example, ammonia at 10 OU/ m^3 has the same character as ammonia at 100 OU/m^3. The fourth column of Table 2.1 describes the character of some selected odourants. Some of the descriptive words listed in Table 2.1 refer to pleasant responses. Many alcohols and ketones have sweet and fruity descriptors. Farmstead odours are combinations of various odourants. An odourant by itself may be pleasant, but it can be unpleasant when combined with other compounds. Surprisingly, indole, a nitrogen-containing compound described in Table 2.1 as having a 'fecal' odour is a major component in jasmine-scented perfumes. With two methods we can quantify or assign a numerical value to odour character. These methods are offensiveness and hedonic tone. Normally, in an olfactometery laboratory, panelists can recognize the character of odour samples based on an odour descriptor table (McGinley et al. 2000).

2.1.6 Hedonic Tone

Hedonic tone is a measure of the pleasantness or unpleasantness of an odour sample. Pleasant odours have positive hedonic tones, and negative hedonic tones indicate unpleasant odours. A common scale for ranking odours by hedonic tone has 10-point scale:

+5….. Extreme pleasant
+4…...Very much pleasant
+3….. Moderate pleasant
+2….. Slight pleasant
+1….. Very slight pleasant
0….. Neutral
-1….. Very slight unpleasant
-2….. Slight unpleasant
-3….. Moderate unpleasant
-4…...Very much unpleasant
-5… Extreme unpleasant

The average value obtained from the odour panel is the hedonic tone for a particular odour sample. Table 2.4 shows as an example how an olfactometry laboratory evaluated the hedonic tone of the odour sample. The panel included seven people, and the average

hedonic tone calculated was -2.9.

Table2.4 Evaluation of hedonic tone in the olfactometery laboratory of the University of Alberta

Number	Name of panelists	Hedonic tone
1	A	-2
2	B	-2
3	C	-3
4	D	-1
5	E	-4
6	F	-3
7	G	-5
	Ave.	-2.9

2.2 Treatment Methods

2.2.1 Introduction

Air VOCs and VIOCs' can be reduced by chemical and biological methods. Some chemical control options can be utilized in order to decrease or exterminate odours in collection systems and treatment plants. The majority of these chemicals are used to treat odourous sulfide compound, however, a few are designed to treat organic odourants. Even though chemicals have been used successfully to control odours in many applications, a thorough evaluation of all odour control options must be done prior to selecting chemical treatment. Each case is unique with site-specific parameters that may or may not make chemical treatment suitable or economical. The rate of contaminated airflow and the concentration of odourants can affect the choice of technology (Table 2.5). However, when the evaluation verifies that chemical control options should be taken into consideration, the consequences can be economical and effective (ASCE, 1995).

The treatment units in which the chemical and biological reactions take place have been developed in several forms. However, biofiltration appears to be the most appropriate technology for animal facilities.

Table 2.5 Range of concentrations of odourants and flow rate for various technologies (adapted from Govind, 2001; Devinny et al., 1999; ASCE, 1995; O' Neil et al., 1992)

Method and principle of operation	Range of airflow rate	Concentration of odourant
Condensation: (increasing pressure at a uniform temperature or decreasing temperature at a uniform pressure)	200-20,000 m^3/h (120-12,000 SCFM)	50-200 g/m^3 (2.8-11.2% by volume)
Cryo-condensation: (increasing pressure and cooling)	30-600 m^3/h (20-400 SCFM)	5-90 g/m^3 (0.28-5% by volume)
Scrubbing: (using water or chemicals)	200-20,000 m^3/h (120-12,000 SCFM)	10-40 g/m^3 (0.56-2.3% by volume)
Thermal incineration: (Oxidation at 700 °C)	10,000-100,000 m^3/h (6,000-60,000 SCFM)	8-140 g/m^3 (0.5-8% by volume)
Catalytic oxidation: (Oxidation at 400 °C)	10,000-100,000 m^3/h (6,000-60,000 SCFM)	1-10 g/m^3 (500-6,000 ppmv)
Regenerative adsorption: (using activated carbon and treating the odourants)	100-10,000 m^3/h (60-6,000 SCFM)	1-10 g/m^3 (500-6,000% ppmv)
Non-regenerative adsorption: (using activated carbon)	10-60 m^3/h (6-40 SCFM)	0-5.0 g/m^3 (<1-2,800 ppmv)
Compost biofilter:	60-300,000 m^3/h (40-180,000 SCFM)	(<1-25 ppmv)
Biotrickling filter and bioscrubber:	10-300,000 m^3/h (6-180,000 SCFM)	0-8.3 g/m^3 (20-5,000 ppmv)

2.2.2 Biological Treatment

Biofiltration technology relies on microorganism activities and is being recognized as one of the most beneficial methods to change pollutants to harmless products. Generally, the microbes used for biological treatment are organisms that occur in nature. Biological treatment is effective and economical for low concentrations of pollutant in large volumes

of air (Figure 2.3). This figure shows that the range of concentration suitable for biological reactors is between 0 to 5 g/m^3.

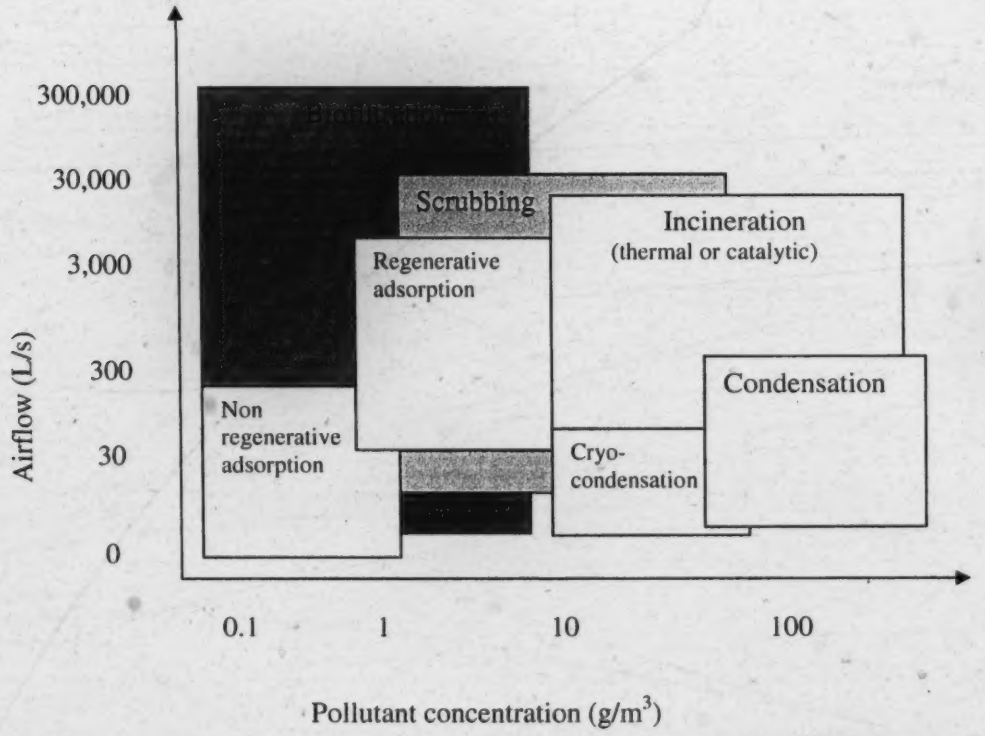


Figure 2.3 Applicability of a variety of air pollution control technologies based on airflow rates and concentrations of odourants to be treated (adapted from Kosteltz, et al., 1996; Deshusses and Cox, 2004)

The VOCs and VIOCs in the air are utilized as energy and possibly as a carbon source to maintain and grow microorganism populations. Biodegradability of various contaminants in a biofilter is different; the most successful removal occurs for low molecular weight and highly soluble organic compounds with simple bond structures. Compounds with complex bond structures generally require more energy to be degraded, and this energy is not always available to the microbes. Hence, little or no biodegradation of these types of compounds occurs. Instead, microorganisms degrade those compounds that are readily available and easier to degrade (Caunt et al., 1999; Devinny et al., 1999; Martin et al., 1992). There are only three types of bioreactors that are well established for odour

control: bioscrubbers, biofilters, and biotrickling filters. These reactors will be described later.

2.2.2.1 Effectiveness and Costs of Biofiltration

The effectiveness of a biofiltration technology can be defined by the flow rates and concentrations of the gases that should be treated. For all technologies of odour reduction, cost-effectiveness depends on the particular application, waste stream to be treated, materials necessary for construction, monitoring systems, etc. Menig et al. (1997) reported that the capital and operating cost of biofiltration technology is lower than other odour removal technologies such as adsorption and catalytic oxidation. However, Figures 2.4 and 2.5 show the differences in capital and operating costs for biofiltration when compared with incineration and adsorption.

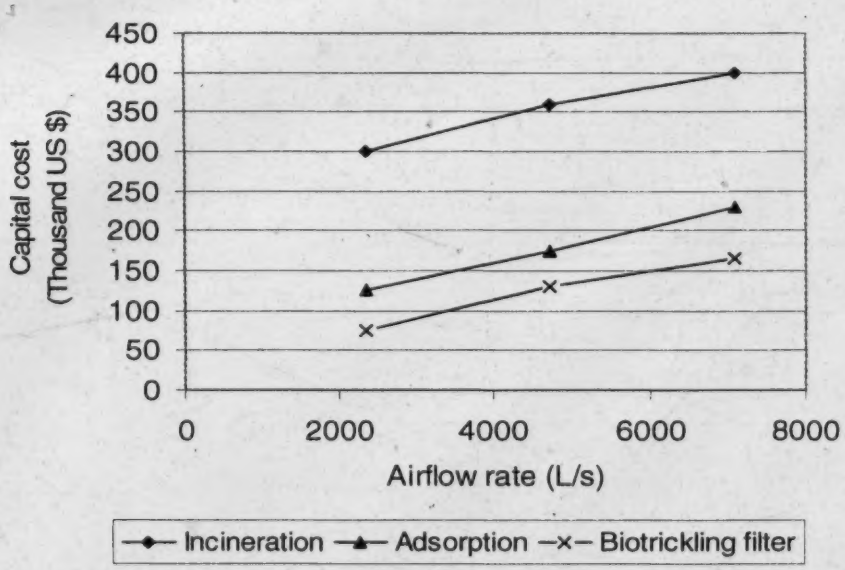


Figure 2.4 Investment costs vs. airflow rate for various air pollution control technologies (modified from Govind, 2001)

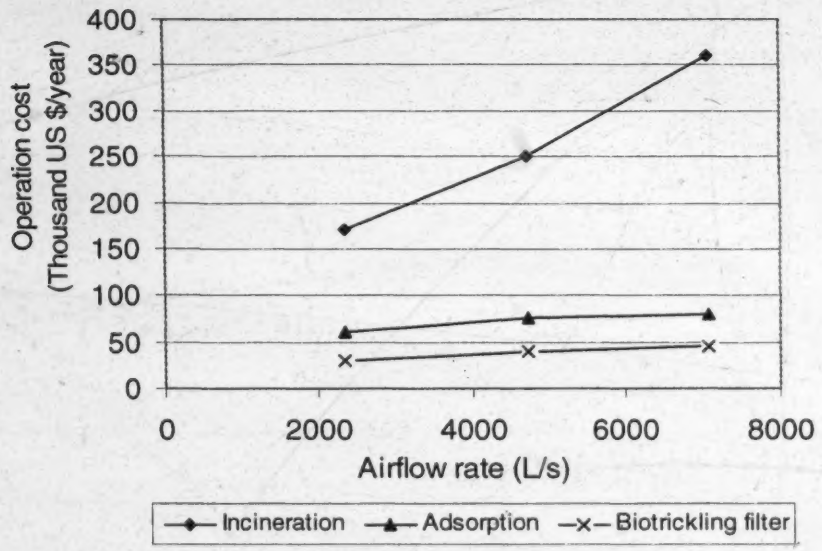


Figure 2.5 Operating costs vs. airflow rate for various air pollution control technologies (modified from Govind, 2001)

2.2.2.2 Biofiltration Theory

Biofiltration is a technology that utilizes microorganisms (bacteria, fungi and actinomycets) immobilized in a biofilm (a wet biologically active layer) on the surface of the filter media. When contaminated air is forced through the biofilter material, basically two removal mechanisms (absorption/adsorption and bio-oxidation) occur simultaneously. With enough residence time the odourants diffuse into biofilm. Then, under aerobic condition, they will be oxidized to CO_2, H_2O, microbial biomass and other by-products such as nitrite and nitrate (Devinny et al., 1999; Ottengraf 1986).

The biofilter's media acts as a source of nutrients (organic and inorganic) for the microorganisms, thereby supplementing those nutrients that may or may not be present in the gas stream being treated (Ottengraf, 1986). Adsorptive sites on the biofilters become available for additional odourous compounds in the gas stream as odourous compounds become oxidized; thus self-regenerating the filter's odour removal capacity.

The microbial degradation rate of the sorbed odourants must equal or exceed the absorption/adsorption rate in order to maximize odour removal rates in a steady-state

operation condition. If filters are fully saturated with odourants (Figure 2.6, Case 1), elimination of the pollutant is limited by the biological activity in the film, with the assumption that the gas film resistance is negligible. When the biofilm is no longer fully penetrated with the odourous material (Figure 2.6, case 2), the removal of pollutant will be limited by diffusion in the biofilm. If filters are overloaded, absorption sites are filled faster than they are degraded, causing breakthrough of odourous gases into the atmosphere (Bohn and Bohn, 1986).

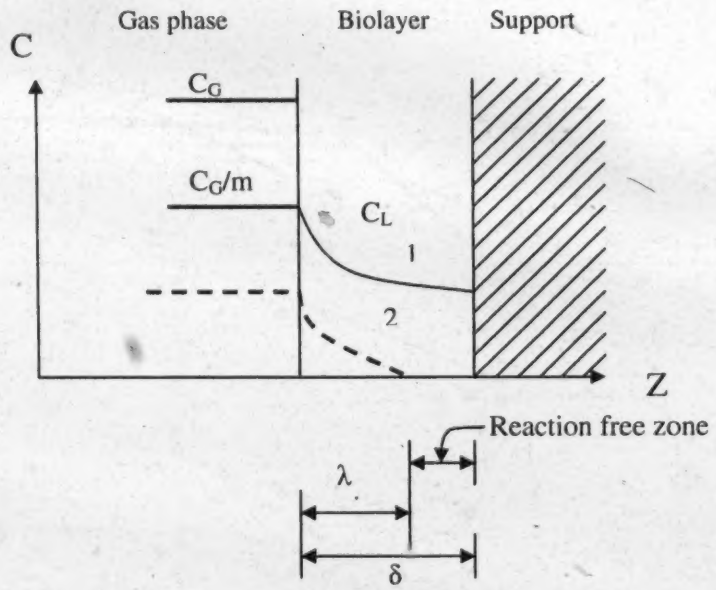


Figure 2.6 Biophysical model and diffusion reaction for the biofilm: λ is the effective biofilm thickness, δ is the biofilm thickness, m is the air/biofilm partition coefficient, C_G and C_L are the concentration in the gas and liquid phases, respectively (adapted from Ottengraf, 1986)

2.2.2.3 Biodegradability of the Odourants

Biofiltration is capable of biodegrading a wide variety VOCs and VIOCs. Biodegradability of these compounds is summarized in Table 2.6. There are three categories of degradability of odourous compounds, including:

1. Material with low biodegradability, such as methane, pyridine, and methyl mercaptan.

2. Moderate biodegradability, such as benzene, carbon disulfide, dimethyl sulfide and dimethyldisulfide.

3. Good biodegradability, such as ammonia, hydrogen sulphide and phenol.

Table 2.6 Biodegradability of various contaminants in a biofilter (modified from Devinny et al., 1999; Govind, 2001)

Contaminant	Biodegradability*	Contaminant	Biodegradability
Aliphatic hydrocarbons (methane, propane, etc.)	1-2	Alcohols	3
Aromatic hydrocarbons (benzen, phenol, etc.)	2-3	Aldehydes	3
Chlorinated hydrocarbons		Carbonic acids (esters)	3
Carbon tetrachloride	1		
Chloroform	1		
Dichloromethane	3		
Nitrogen containing carbon compounds		Inorganic compounds:	
Amiones	3	Ammonia	3
Aniline	3	Hydrogen sulfide	3
Nitriles	1	Nitrogen oxide	1
Sulfur containing compounds	1-2	Ketones	3
		Acetone	3
		Methyl ethyl ketone	3

* There are three categories of degradability of odourants including: 1 (Low i.e. methane); 2 (Moderate i. e. Benzene; methyl mercaptan); 3 (Good i. e ammonia hydrogen sulfide).

2.2.2.4 Application of Biofiltration Technology

Biofilters have the greatest potential for cost-effective operation when it is necessary to treat moderate gas flows containing low concentrations of contaminants. They have been used successfully in a wide variety of settings for odour control and/or control of toxins

in different areas such as waste management, food industries, chemical and pharmaceutical manufacturing, contaminated site reclamation, livestock production facilities, food processing, oil, gas, and petrochemical sector (Son et al., 2005; Devinny et al., 1999 Coleman et al., 1995; Dawson, 1993; Leson and Winer, 1991; Paul and Roos, 1989, Werner et al., 1986; van Eyk and Vreeken, 1991) (Table 2.7). Moreover, biofilters with special design are used in the area of aquaculture. They used in hatcheries (fish and shrimp) and intensive fish farming with circulating water systems. The dissolved oxygen, pH and concentrations of NH_3, NH_4^+, NO_2^-, and NO_3^- are the important factors that should be controlled in the fish pond because fish are very sensitive to the toxicity of the NH_3 and NH_4^+. By using biofilters in the water system we can reduce the toxicity of ammonia and ammonium and VOCs concentrations. However, by controlling the VOCs and VIOCs the dissolved oxygen will be stabilized.

Table 2.7 Examples of biofilter applications (adapted from Coleman et al., 1995)

Commercial	Industrial/Manufacturing	Waste Management
1. Printing 2. Painting 3. Food production and processing: baking, meat processing, coffee roasting, coca roasting, fish frying, slaughter houses, tobacco processing, rendering, pet food manufacturing, flavours and fragrances, feed lots, barn	1. Foundries 2. Photographic industry 3. Chemical and petrochemical manufacturing (paints, inks, glues, polymers, resins, rubber, plastics) 4. Pharmaceutical manufacturing 5. Petroleum and chemical storage tanks 6. Flavour and fragrance industry 7. Coating industries (plastics, wood, metals)	1. Landfill gas extraction 2. Composting operations 3. Sewage and waste water treatment plants (residential and industrial) 4. Soil vapour extraction 5. Hazardous waste storage and recycling

2.2.2.5 Comparison of Common Biofiltration System

Three types of biofiltration systems for controlling odours are: biofilters, biotrickling filters, and bioscrubbers (Figure 2.7). The basic removal mechanisms are alike for all reactor types. However, differences exist in the phase of the microbes, which may be suspended or fixed, and the state of the liquid may be flowing or stationary (Caunt et al., 1999; Devinny et al., 1999; Martin et al., 1992). Table 2.8 provides a classification of bioreactors based on the state of liquid and microorganisms.

Table 2.8 Classification of Biofiltration systems for purification of the waste gases (adapted from Devinny et al., 1999)

Reactor type	Microorganisms	Water phase
Biofilter	Fixed	Stationary
Biotrickling filter	Fixed and suspended	Flowing
Bioscrubber	Suspended	Flowing

Biofilters normally operate with a humidifier for increasing the moisture content. They consist of one or more layers of material. Biotrickling filters are similar to biofilters except moisture is added from the top of the filter and allowed to trickle down through the media. Generally, a greater than biofilter media porosity is needed for air to pass through the media and to prevent pooling or plugging. High porosity, wet-scrubber type material is used rather than compost, peat moss, or other organic material. A biotrickling filter has a recirculating liquid flow over the media either co-current or counter current to the flow of air. Bioscrubbers usually consist of two interconnected units. In the first unit, gas phase contaminants are transferred to the water by passing the air through a combination of water, support media, and biomass. In the second unit under aerobic condition, odourants will be degraded. Table 2.9 shows the advantages and disadvantages of each configuration. The main criteria for selection of configuration include the space availability, capital and operation costs, maintenance requirements, and filter media selected (Leson and Winer 1991). In the following, the biofilters, biotrickling filter, and bioscrubbers will be discussed.

Table 2.9 Advantages and disadvantages of different biofiltration systems for odour reduction (modified from Leson and Winer, 1991; Devinny et al., 1999)

Biofilters	
Advantages	Disadvantages
Simple operation and start up Low capital and operating costs Suitable for reduction of low concentration of odour Low pressure drop No further waste streams produced	Less suitable for high odourous concentrations Moisture and pH difficult to control Particulate matter may clog medium Channeling of airflow develops
Biotrickling filters	
Advantages	Disadvantages
Simple operation and start up Medium capital and operating costs Suitable for reduction of moderate odour concentration pH control possible Ability to control by-products, and add nutrients Low pressure drop	Clogging by biomass Limited process control Wash out of slow growing microorganisms Possibility of channeling
Bioscrubbers	
Advantages	Disadvantages
Good process control possible High mass transfer Suitable for highly contaminated air High operational stability Ability to add nutrients	High capital and operation costs Excess biomass produced Water disposal Possible plugging in adsorption stage

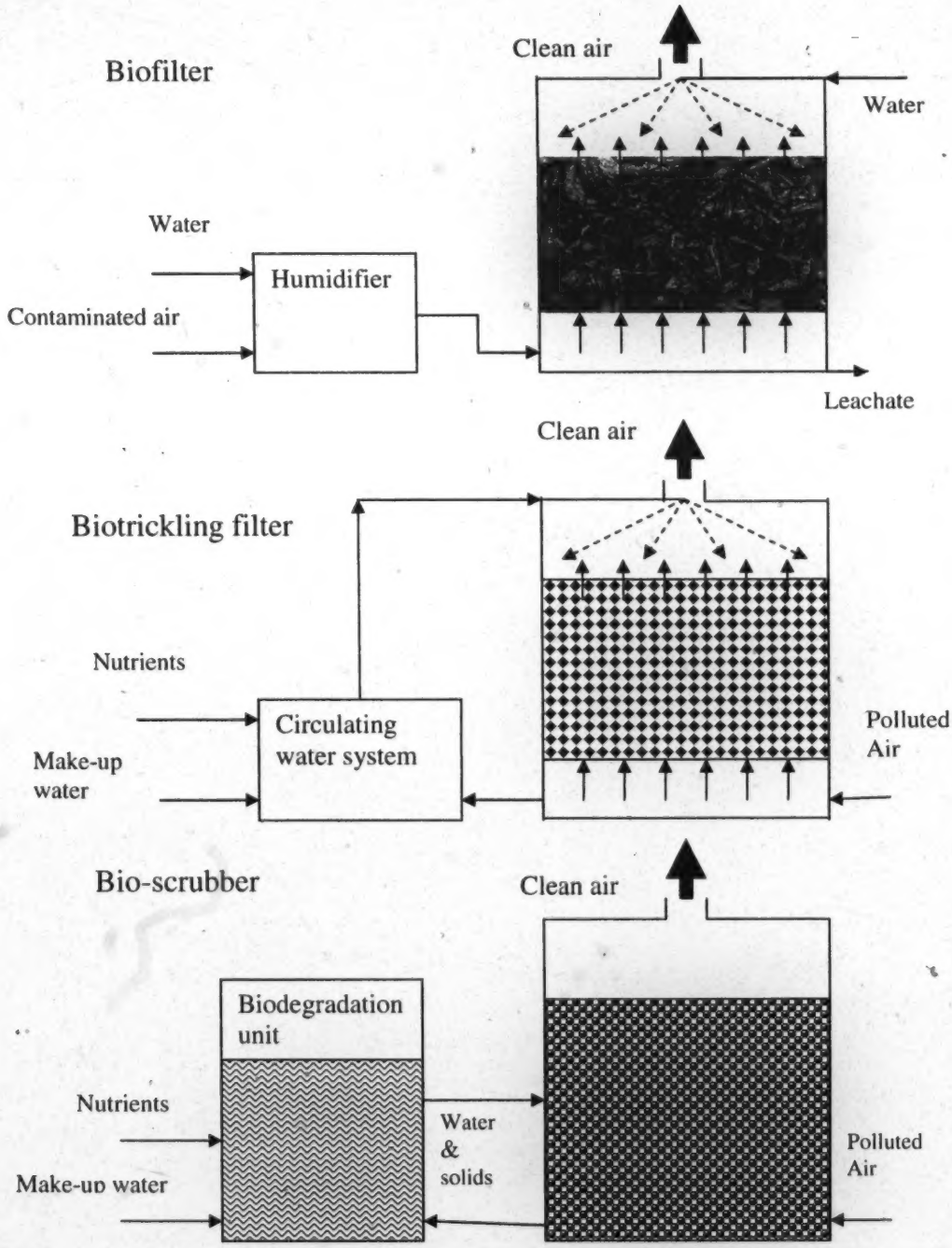


Figure 2.7 Schematic diagrams of the three categories of biofiltration system (modified from Edwards and Nirmalakhandan, 1996)

2.2.2.5.1 Biofilters

As mentioned earlier, biofilters are an air pollution control technology that takes advantage of microorganisms for oxidizing VOCs and oxidizable inorganic gases in contaminated air. Biofilters can be designed in two configurations: closed and open (Figures 2.7 and 2.8). Pollutants are passed over to the microorganisms by moving the contaminated air through the biofilter matrix, permitting the diffusion of contaminants into the biofilm. Target compounds such as low molecular weight inorganic and volatile organic compounds, including low molecular weight organo-sulphur compounds, have shown to be removed with great efficiency (Chen et al., 2004; Filson et al., 1996; Coleman et al., 1995; Bohn and Bohn, 1986). Bioscrubbers and biofilters have revealed removal efficiencies of 90% to 95% for alcohols, aldehydes, ammonia, ethers, and sulfides. Over 90% removal has been reported for ethyl acetate, methyl methacrylate, ethanol, butyraldehyde, styrene, butadiene, acrylonitrile, vinyl cyclohexane, formaldehyde, and butyl cellulsolve (Caunt et al., 1999).

Biofiltration is an effective and inexpensive technology to decrease odour, hydrogen sulfide, and ammonia emissions from livestock facilities (Vansickle, 1999; Nicolai and Janni, 1997; Noren, 1985). One advantage of the use of biofilters is that low concentrations of odorous effluent gases can be processed at low operation and maintenance costs. The filter material on which the microorganisms are immobilized has to allow easy passage of moisture and effluent gases, and also has to provide good conditions for microbial growth (providing nutrients). Residence time in the biofilter must be controlled so that odorous pollutants have time to diffuse into the biofilm and be degraded. Due to the relatively slow rates of biological degradation, this time is generally longer than for other methods of odour control. Biofilters can remove contaminants at low concentrations because of the large effective surface available for mass transfer. They are also able to cope with disturbances in airflow rates and pollutant concentrations (Caunt et al., 1999; Williams and Miller, 1992; Martin et al., 1992).

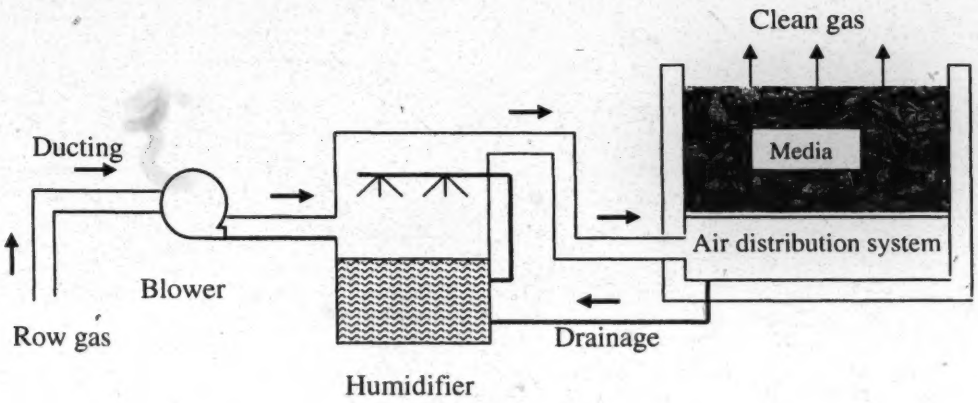


Figure 2.8 Schematic of an open single bed biofilter system (modified from Leson and Winer, 1991)

Biofilters are useful for treating streams with low VOC concentrations. They are typically recommended for use with streams containing less than 0.01-5 g m^{-3} or 500-50,000 OU/m^3 of easily biodegraded air pollutants. Ethers, alcohols, aldehydes, ketones, and several common monocyclic aromatics are generally well degraded. Highly chlorinated organics tend to degrade with a slower speed. Thus, biofiltration may not be appropriate for streams containing chlorinated organics (Devinny, et al., 1999; Martin et al., 1992).

2.2.2.5.2 Biotrickling Filters

In biotrickling filters, odourous contaminants are absorbed in a free liquid phase prior to biodegradation by either immobilized or suspended microorganisms. Similar to bioscrubbers, liquid is sprayed on the top of the packed media and will be circulated continuously. Biotrickling filters work with the air and water phases moving either counter-currently or co-currently, depending on the exact operation. While the water is circulating, the operator can add nutrients, acids, or bases to control the environment for having optimal pollutant elimination (Caunt et al., 1999; Devinny et al., 1999; Keller and Dyer, 1997). In contrast to biofilters, recirculation of water in trickling filters provides more homogeneity of availability of nutrients and moisture contents in the packing media.

2.2.2.5.3 Bioscrubbers

In a bioscrubber, after absoption of odourants in the first stage (packed column, spray tower, or a bubble column) the liquid is transferred to another vessel where optimum environmental conditions for degradation are maintained. Then, the degradation of the compounds is performed by a suspended consortium of the microorganisms under aerobic condition. This second vessel should be properly aerated to ensure that degradation of the contaminant takes place (Devinny et al., 1999; Caunt et al., 1999). In contrast to biofilters and similar to biotrickling filters, recirculating of the liquid in the bioscrubber allows a better control of the important operating parameters such as providing nutrients, pH, byproducts etc. The second step of the process in the bioscrubbers is similar to the second step of a wastewater treatment plant process. With good design, bioscrubbers are capable of treating air containing higher concentrations of odourants than 8 mg/m^3. To sustain the organisms in an active condition, primary or secondary wastewater effluent from the biodegradation unit is sprayed on the packing material. The effluent provides the biomass with the moisture and nutrients necessary for survival (Martin et al., 1992).

2.2.2.6 Biofiltration Operational Factors

The successful design and operation of a biofiltration system requires consideration of a number of technical factors, which are presently listed.

Biofilter media
Microorganisms
Moisture content (MC)
Oxygen
Temperature
pH
Medium depth and pressure drops
Nutrients
Contaminant load
Toxic and inhibitory by-products removal
Dust and grease of the contaminated air

The most important parameters for an efficient biofilter are medium pH, moisture content, bed temperature, nutrients, contaminant load, and controlling by-products.

2.2.2.6.1 Biofilter Media

The choice of media for odour removal strongly affects biofilter performance. The main characteristics of a good medium include high surface area, minimum pressure drop and an appropriate surface for microbe attachment (Sorial et al., 1995). The biofilter material must also have the ability to adsorb the pollutants, provide good airflow characteristics, and be as cheap as possible (Medina et al. 1995). Moreover, the biofilter materials should have high moisture retention capacity to prevent drying and sufficient nutrients for optimal microbial growth. Multiple beds are often used because the pressure drops become excessive, requiring large energy inputs for the blowers when bed heights exceed one meter (Son et al., 2001; Devinny et al. 1999). Inert materials generally serve multiple purposes. One of their fundamental functions is preventing compaction in biofilter beds and minimizing the pressure drop. Big size inert media such as expanded polystyrene, glass, perlite, vermiculite, tire scraps, etc., have been utilized for this purpose (Weber and Hartmans, 1995). These materials are often called bulking agents. It is also desirable for the filter materials to have a significant pH buffering capacity to prevent acidification due to by-products (Leson and Winer, 1991). The other materials, such as compost, peat moss, wood chips or barks, activated carbon, soil, etc., can be used as the biofilter media. Table 2.10 shows a comparison of some biofilter media.

Table 2.10 Comparison of biofilter media (Modified from Devinny et al. 1999; Edwards and Nirmalakhandan, 1996)

Media	Advantages	Disadvantages
Compost/Peat	High population of microorganisms Suitable for low concentration VOCs Low cost High to medium nutrients Lifetime 2 to 4 years High absorption of water	Compaction and channeling Limited buffer capacity Low biodegradation capacity
Granular activated carbon Packed bed	High adsorption Good biomass adhesion Fast start up (adsorption) Suitable for high contaminant concentrations High biodegradation capacity Lifetime > 5 years	High cost Difficult to clean because of strong adhesion No nutrients
Pelletized ceramic	Easy to clean Less expensive than activated carbon High biodegradation capacity	More expensive than compost or peat
Perlite, and other inert materials	High surface area Lifetime > 5 years	Medium cost No availability of nutrients

2.2.2.6.2 Microorganisms

Several groups of microorganisms are known to be involved in the degradation of air pollutants in biofilters, including bacteria, fungi, and actinomycetes.

Bacteria are the major group with a wide variety of forms that thrive under different environmental conditions. They are the smallest of the above organisms and have the ability to degrade air contaminants faster.

Fungi are bigger organisms, and they are more tolerant than bacteria to low moisture content and low pH of the media. However, they are less tolerant of low oxygen concentrations in the environment. Actinomycetes are similar to fungi, but they are small in size and are technically classified as bacteria. They tend to become more pronounced when the easy degradable compounds have been degraded. Like fungi, they have more

tolerance to low moisture condition than bacteria. However, they have a low tolerance for acidic conditions. When biofilters contain organic media with low moisture content, fungi and actinomycetes are more active (Metcalf and Eddy 1991; Atlas and Bartha, 1993). Ottengraf and van den Oever (1983) and Eitner (1984) have investigated the distribution of microorganisms within biofilters, and they have observed that the density of microorganisms is greatest where VOCs removal is highest. Typically, compost materials in the biofilters have significantly higher population densities of microorganisms than soil (Devinny et al., 1999; Eitner 1984). Biofiltration relies mainly on heterotrophic organisms that use organic materials as carbon and energy sources. Consequently, introduction of these compounds into the biofilter materials upon start-up will generally shift the distribution of existing microbial populations towards strains that can metabolize the target pollutants (Leson and Winer, 1991).

Acclimation time is the time that a biofilter needs to reach a steady state condition or maximum removal efficiency after starting-up. Different factors affect the acclimation time, including property of specific compounds, the complexity of a gas stream (number of chemicals), and characteristics of the biofilter media. However, more than 10 days is generally required to allow microbial acclimation to treat the specific waste gas streams (Ottengraf, 1986).

2.2.2.6.3 Moisture Content

Moisture content of the biofilter media is an essential operational parameter, which must be controlled to achieve optimal filter performance. A dry biofilter medium can cause a severe reduction in microbial activity and poor treatment of the odourous gases. Also, the drying of the biofilter media causes channeling and shrinkage of bed material. In reverse, operating the biolfilters with high moisture content will cause clogging, increase the pressure drop, and favour development of anaerobic conditions (Devinny, et al., 1999). Optimal moisture content within the filter ranges between 40 to 60% on a wet weight basis (Chan and Zheng, 2005; Leson and Winer, 1991; Ottengraf, 1986). Leson and Winer (1991) suggest a surface water spraying system to provide adequate moisture for biofilter media. A common standard for the utilization demand of water in biofilters is between 22 and 45 litres per 2,830 m^3 of gases being treated (Leson and Winer, 1991;

Randa et al., 1991; Bohn and Bohn, 1986). The medium should have good water absorbability to store large quantities of water and make it easily accessible during periods of drying. Nonetheless, it is desirable to have media with a high capacity for holding water, and typical organic media with a high water-holding capacity may absorb 40 to 80% water (by wet weight) when they are saturated (Devinny, et al., 1999). The amount of water essential to complete a monolyer varies with the surface area of the medium. For example, in fine clays, which have very high surface areas per unit volume, a monolayer of water may represent a water content of 10% by weight (Devinny, 1989). A monolayer of water will constitute much less than 1% by weight in large-particle sands with low specific surface areas (Devinny et al., 1999). See chapter 7 for more details on water application.

2.2.2.6.4 Availability of Oxygen

Oxygen limitation may occur in the biofilm during high performance of biofilters.

Initially, the existence of oxygen limitation in an air biofilter might seem contradictory because 21% of air is oxygen. The oxygen gas-liquid partition coefficient is 33.5, meaning that most of the oxygen is in the gas phase rather than dissolved. For example, at 25°C, the dissolved oxygen concentration in equilibrium with air is about $8.1 mgL^{-1}$, but increasing the performance of biofilter can create an imbalance between the rate of dissolved oxygen and consumption (Devinny et al., 1999). Anaerobic zones caused by high water contents, media compaction, biomass build up (clogging), or channeling of the air stream should be prevented. Shareefdeen and Balzis (1994) found that low water soluble VOCs were depleted before the gas oxygen exhausted in the biolayer attached to the support media such as peat and perlite. Hydrophilic VOCs, such as methanol, ethanol, and n-butanol, consumed the available oxygen before complete degradation could happen. Athough some chlorinated compounds are degraded better under anaerobic conditions, generally oxygen deprived situations should be avoided because the majority of VOCs are more easily oxidized than reduced anaerobically. Also, anaerobic activity is typically much slower than aerobic and anaerobic biofilters have the potential to produce malodourous gases (Yang and Allen 1994). A minimum of 100 parts of oxygen should be provided for each part of oxidizable gas to ensure sufficient supply exists (Williams and

Miller, 1992). Oxygen is an important necessity for an aerobic biofilter. With most reactors, the biofilm layer becomes thick enough to support both an aerobic and an anaerobic microbial population. Anaerobic zones, however, caused by biomass build up, high water content media compaction, etc., should be prevented.

2.2.2.6.5 Temperature

Microbial activity and biofilter success are greatly influenced by temperature. Biological activity increases by a factor of roughly two for each 10°C rise in temperature, up to an optimum of about 37°C. Inlet air may require heating or cooling to ensure that good operating conditions are provided. Operating temperatures of between 10°C and 40°C have been recommended (Devinny et al., 1999; Coleman et al., 1995; Williams and Miller, 1992; Leson and Winer, 1991). Figure 2.9 shows the overall effect of temperature on microbial activities.

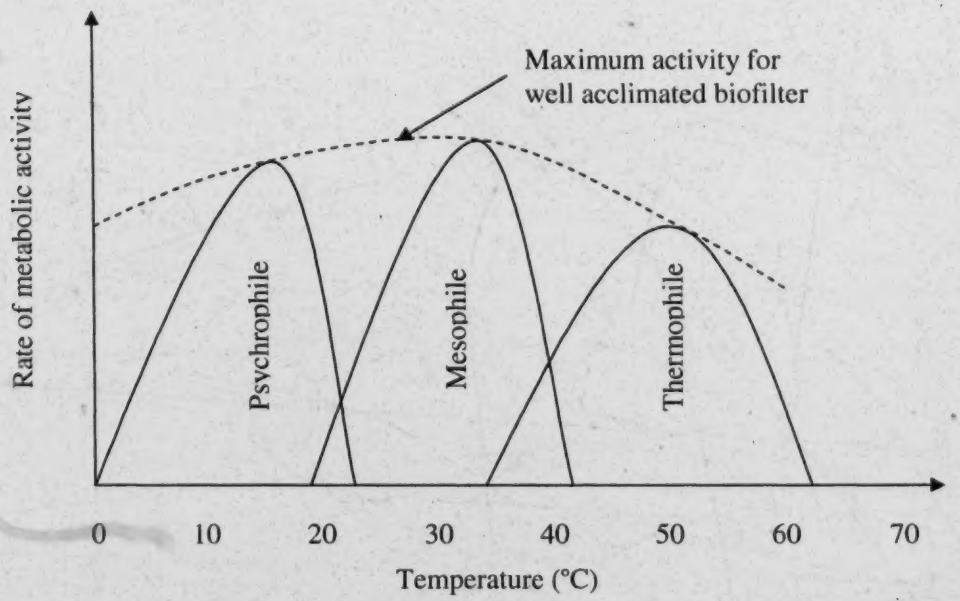


Figure 2.9 The effect of temperature on microbial activity in the biofilter (modified from Devinny et al., 1999)

2.2.2.6.6 pH

The pH value is not only an important design parameter, it is also a characteristic of a

specific bioreactor system (Coleman et al., 1995). Since biofilters operate on the basis of microbial activity, the pH must be maintained at or around neutral to assure maximum microbial activity leading to maximum odour treatment. Most biofilters are built for operation near pH 7. However, it is important to know that microorganisms are abundant and active in many natural ecosystems where the pH is lower or higher (Devinny et al., 1999; Leson and Winer, 1991). The oxidation of sulphur-, nitrogen- and chlorine-containing compounds produces acid that lowers the pH and can decrease the biomass effectivness (Coleman et al., 1995). Various biofilters may function with different ideal pH values, depending on the contaminant being treated and the characteristics of the microbial ecosystem (Table 2.11) however, alterations in pH value usually cause stress for the microorganisms. A near neutral pH is a necessity for the greatest spectrum of bacterial activity. Although in some cases, for example when treating reduced sulfur compounds, a pH of 2 to 4 has been observed. The usual pH value for packing materials is 6 to 8 (Devinny et al. 1999). However, Leson and Winer (1991) reported that the optimum pH for biofilter operation is in the range of 7 to 8.

For measuring pH of a biofilter media approximately 5 g of the media is weighed into a container (175 ml). Dilute the sample with 20 ml. Stir the mixture for 5 minutes and measure the pH of the mixture. Then, add 20 or 40 ml DD water. Stir the mixture for another five minutes and measure the pH of the mixture. Finally, due to the linear relationships existing between the dilution ratios and pH values, the pH of the media can be obtained at the intercept. However, because different factors can affect the pH of the biofilter media at different depths of the media in this experiment, we focus on the pH of the leachate of the biofilters.

Table 2.11 pH ranges for nitrifying bacteria and thiobacillus (Atlas and Bartha, 1993)

Species of microorganisms	Miniumum	Optimum	Maximum
Nitrosomonas spp.	7.0 to 7.6	8.0 to 8.8	9.4
Nitrobacter spp.	6.6	7.6 to 8.6	10.0
Thiobacillus thiooxidans.	1.0	2.0 to 2.8	6.0

The pH of an environment can directly affect microorganisms and microbial enzymes. The pH value also indirectly influences the accessibility of required nutrients. For instance, ammonium and phosphate, as well as the dissociation and solubility of many molecules, indirectly limit microbial growth (Atlas and Bartha, 1993). The pH level directly affects the fraction of free ammonia in the aqueous system. pH above 7 leads to a higher fraction of free ammonia, which can be released from the liquid (Metcalf and Eddy, 1993; Zhang et al., 1993).The pH value affects the ionic equilibrium of H_2S in the biofilter liquid; when the solution pH increases, the concentration of H_2S in the liquid decreases and the concentration of the HS^- increases. This is an important concept because a decreased H_2S concentration in the solution allows for more absorption of gaseous H_2S from polluted air according to Henry's Law.

2.2.2.6.7 Pressure Drop

The biofilter materials should remain stable with time. To obtain a stable condition of biofilter operation, no clogging or shrinking of the medium due to the decomposition, compaction of materials, or water condensation should occur. A medium that is heavy and soft will compact at the bottom if the layer of material is too deep. Compost mediums have a lower density of 300 to 500 kg/m^3 (wet) but are easily compacted. Thus, there is a limitation of layer height of 1 to 1.5 m for low-range compaction (Devinny et al., 1999). Leson and Winer (1991) recommend that the range of biofilter medium depth should be between 0.5 to 2.5 m. Moreover, they mentioned that a depth of about 1 m appears to allow sufficient residence time while minimizing filter floor area requirements. The porosity of the media can vary over time because of moisture content alterations, microbial degradation of the support matrix, and potential compaction and settling. Changes in porosity are likely to affect gas pressure required to force the waste gases through the system. Continual monitoring of the pressure drop across the filter materials is a key factor for controlling the biofilter and in helping the operator to adjust the amount of airflow or mass loading of the pollutants. However, care must be taken to resolve pressure drop related to the design of the system (Higgins et al, 1982). The pressure drop is a very critical operating factor, since the operating cost is proportional to the pressure drop across the biofilter bed. Normally, in a typical biofilter bed, the total

pressure drop is less than 75 Pa (Govind, 2001). The expected pressure drop through the biofilter is determined by knowing the percent of void space of the media and the airflow rate (Figure 2.10). In the field, the following procedure can be used to determine void space of the biofilter media such as compost-wood chip (Nicolai, 1998). However, three straight lines on the above figure show the maximum, minimum, and optimum void space is needed for the compost media.

a) Check the volume of the 20L pail by filling it with 20L of water and marking the "fill line" on the pail (put the 20L pail on a flat concrete floor at room temperature. Then, with a smaller container, (2L) add 20L water to the container and wait 2 minutes. Then, mark the fill line). Then, empty the water and mark four sides of the container at 1/3 and 2/3 height of it.

b) Fill one-third of the pail with media and drop it ten times from a height of 15 cm onto a concrete floor.

c) Add media to fill the pail two-thirds full, and drop the pail ten times from a height of 15 cm onto a concrete floor.

d) Add media to fill the pail up to the "fill line" and drop the pail ten times from a height of 15 cm onto a concrete floor.

e) Add media to fill the pail to the "full line".

Add and keep track of the amount of water that can be added to the pail until it reaches the "full line".

The voids Space (%) = (the amount of water added/ 20)×100

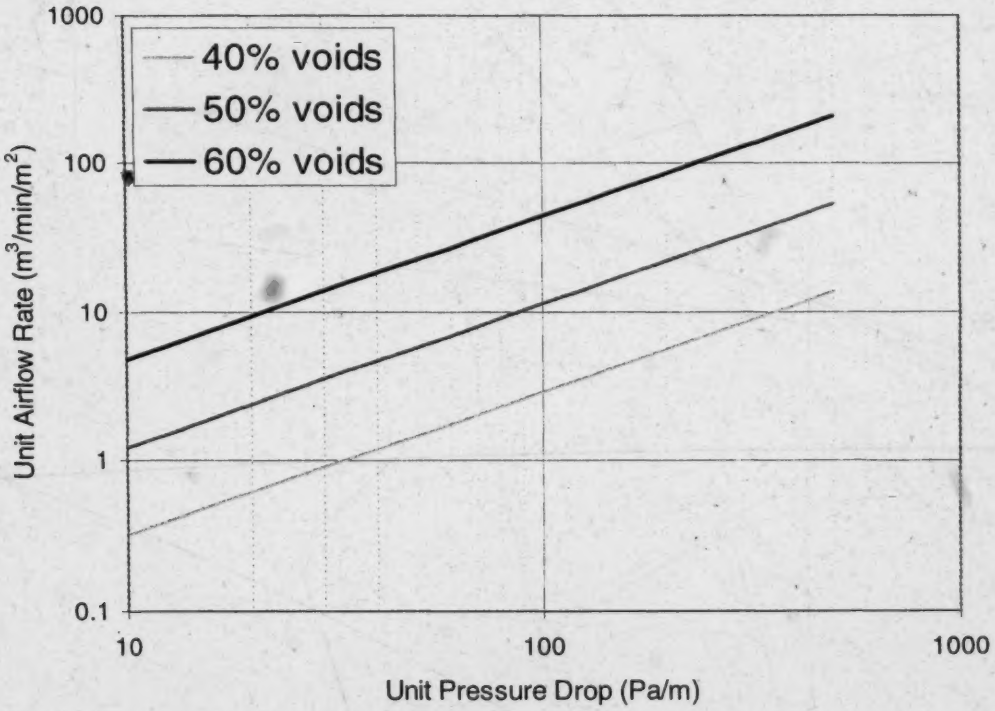


Figure 2.10 Media unit pressure drop and unit airflow rate relations for various percent voids (adapted from Nicolai, 1998)

2.2.2.6.8 Nutrients

Availability of nutrients in biofilters is an important factor that must be taken into consideration. At the moment, not much information exists on nutrient cycles and nutrient requirements in biofilters (Devinny et al., 1999). Two major parameters for the design of a biological treatment process are the nature of microbial metabolism and the general nutritional requirements of the microorganisms. Similar to plants, microorganisms are in need of a source of energy, carbon for the synthesis of new cellular material, and inorganic elements (nutrients) such as N, S, P, K, Mg, Ca, Fe, Na, and Cl to continue reproduction and proper functioning.

Two of the most common carbon sources for microorganisms are organic matter and carbon dioxide. Heterotrophic organisms obtain their required carbon (for the formation of cell tissue) from organic carbon while autotroph organisms use carbon dioxide

(Metcalf and Eddy, 1993). Inorganic nutrients are transported by diffusion from the bed materials to microorganisms. One of the important aspects of the nutrient balance is the ratio of carbon to nitrogen. Since organisms utilize about 30 parts of available carbon for each part of nitrogen, C/N ratio between, 25 to 30 is optimum for microbial activity in the biofilter medium (Biocycle, 1991). However, Gibbons and Loehr (1998) determined that the nitrogen to carbon ratio should be at least 1 to 100.

Compost-based media usually provide enough nutrients (i.e. C/N ratio of 25 to 35) for microorganisms, and therefore the addition of nutrients is not required (Leson and Winer, 1991). However, some researchers (Corsi and Seed, 1995; Morgenroth et al., 1995) report that nutrient availability can sometimes become a limiting factor. Hence, it may be necessary to add nutrients to the biofilter.

Nutrients are generally supplied as slow-release nutrient granules or sprayed as solution onto the medium during initial medium preparation only. However, sometimes nutrients are added afterward on a regular basis during operation. In general, for a compost-based medium, an initial addition of N, P, and K in the range of 0.4, 0.15, and 0.15% by weight based on dry packing is considered sufficient (Devinny et al., 1999).

2.2.2.7 Suitable Treatment Method for VOCs and VIOCs Reduction in Swine Facilities

Livestock buildings require ventilation for controlling environmental factors such as temperature (removal of heat), carbon dioxide, and aerial contaminants. Therefore, exhausted air carries odorous constituents to the surroundings. The most effective way for control is to prevent release and operating a farm well (collecting and transferring the manure on the daily bases for treatment or storage in a covered area). However, selecting an odour control technology relies on the compounds causing the odours and their concentrations, the air stream flow rate, moisture content, and variability. No single method will decrease or completely get rid of odours at every emission point. Cost-effective methods of treating odour, however, should be viable for most sources (Martin et al., 1992; and O'Neill et al., 1992). As mentioned earlier, several of the fundamental techniques that are used for controlling emissions of volatile organic compounds include: chemical or physical treatment, such as incineration (or oxidation), adsorption,

condensation, absorption, and advanced oxidation; biological treatment (biofilters, bioscrubbers and biotrickling filters), and other technologies. Martin et al. (1992) and O'Neill et al. (1992) found that chemical methods are exclusively expensive. Biological treatments and chimneys, although much less expensive, still carried a large overhead per animal. Reviews of the possible methods for decreasing odour from livestock buildings show that biological treatment method such as biofilter, bioscrubber, and biotrickling filter offer the most efficient solution to the problems of odour nuisance from livestock buildings. However, in terms of both capital and annual costs, the cheapest treatment method seems to be biofiltration.

2.2.2.8 Designing a Biofiltration System

Nicolai and Janni (1998) illustrate that biofilters could be cost effective if inexpensive construction and a suitable design are utilized. For a biofilter to be both effective in removing odour and be economical, the biofilter size must be optimized. At present, because there are no two wastes off gases with the same characteristics, such as type of contaminant, concentration, flow rate, temperature, and relative humidity, etc., the ability to design an effective biofilter involves a combination of fundamental biofilter knowledge, practical experience, and bench and pilot-scale testing. Preliminary investigations of the waste stream and primary or pilot scale experiments produce the necessary details to assess the effectiveness of the technology. Moreover, along with modeling, results from such experiments can be incorporated into sizing and designing the biofiltration system.

Various criteria can be used to design biofilters appropriately for the removal of odourous compounds. To describe the mechanisms of biofiltration clearly, general terminology relevant to the field should be well defined. Because the field of biofiltration involves chemistry, microbiology, physics, fluid dynamics, and mathematics, much of the terminology has been taken from these fields. One key factor that is used for designing and operating the biofilters is the off gas flow rate. As a matter of fact, flow rate is a key determinant that affects elimination capacity (EC), removal efficiency (RE), empty bed retention time (EBRT), mass loading, water application, temperature, pressure drop, heat, volume of the media, etc. Though the range of flow rate must be estimated clearly in the

design, the operator must be able to control the airflow easily. Airflow can be measured directly (Chapter 6). However, in livestock building, the maximum ventilation rate dictates the required biofilter airflow rate. The accurate residence time must be conceived for an efficient biofiltration plan. With the lack of sufficient residence time, odours and gases will not be reduced (Nicolai and Janni, 1999).

2.2.2.8.1 Empty Bed Residence Time (EBRT) and True Residence Time

The time (for example 10s) that the air is in contact with the biofilter material is called the residence time, and it not only depends on the media depth, airflow rate, cross sectional area, porosity, and physical properties of the medium, but it also depends on the mass loading and degradability of the odourants and the biofilter's efficiency. The EBRT can be calculated by dividing the volume of the biofilter media by the air flow rate (equation 2-4) (Devinny et al., 1999).

$$\text{EBRT} = \frac{V_{bm}}{Q_1} \qquad (2\text{-}4)$$

Where:

EBRT = empty bed residence time (s); V_{bm} = volume of filter media (m^3) and Q_1 = air flow rate (m^3/s).

Due to the fact that the empty bed residence time is higher than the actual treatment time, the true residence time, which is the actual time a parcel of air remains in the biofilter, will be calculated based on equation (2-5).

$$\tau = \frac{V_{bm} \times \theta}{Q_1} \qquad (2\text{-}5)$$

Where:

τ = true residence time (s); and θ = porosity = volume of void space/ volume of filter material.

In the literature, the terms "empty bed residence time" and "true residence time" are both commonly used. The difference between these two terms is the porosity factor that can be quite substantial. We assume the flow rate for many specific biofilter is fixed. Therefore, volume of the reactor is the only variable that can be affected EBRT. Typical EBRT for commercial and industrial applications ranges from 25s for treating odours and low

concentrations of VOCs to over a minute for high concentrations of VOCs (Leson and Winer, 1991). Residence times reported in the literature for livestock facilities vary from a few seconds to almost one minute. For example, the results of the study by Nicolai and Janni (1999) indicate that a 5s residence time is recommended for designing biofilters on swine and dairy facilities to achieve more than 80% reduction in emissions. However, most researchers believe that the range of EBRT should be 15 to 60s depending on the specific conditions. Many large biofilters are operating in the U.S with 30 to 60s retention times (Devinny et al., 1999).

2.2.2.8.2 Removal Efficiency (RE) and Elimination Capacity (EC)

The performance of a biofilter can be described by removal efficiency (RE) and elimination capacity (EC). RE is the fraction of the contaminant removed by the biofilter (equation 2-6).

$$\mathrm{RE} = \frac{(C_{gi} - C_{go})}{C_{gi}} \times 100 \qquad (2\text{-}6)$$

Removal efficiency is not a complete descriptor of biofilter performance because it varies with contaminant concentration, airflow and biofilter size, and it only reflects the specific conditions under which it is measured.

Where: C_{gi} = inlet concentration (ppmv); C_{go} = outlet concentration (ppmv)

Elimination capacity is the mass of contaminant that is degraded per unit volume of filter media per unit time (equation 2-7). A typical unit for elimination capacity is expressed as $g/m^3/h$.

$$\mathrm{EC} = \frac{(C_{gi} - C_{go})}{V_1 \times V_{bm} \times 10^3} \times Q \qquad (2\text{-}7)$$

Where: Q = air flow (m^3/h); V_1 = the volume of 1 g of gas (for example ammonia) (L) and V_{bm} = filter bed media (m^3)

Elimination capacity is a normalized factor (flow rate, volume of media, and time). However, the elimination capacity may lead to a direct comparison of two biofilters with different sizes (Devinny et al., 1999).

2.2.2.8.3 Mass Loading Rate and Mass Volumetric Loading

The mass of contaminants entering a biofilter is expressed in terms of surface mass loading or volumetric mass loading. Surface mass loading is the amount of contaminants entering the biofilter per unit time and area (equation 2-8). The units of surface mass loading are $g/m^2/h$. The volumetric mass loading is the amount of contaminants that enter the biofilter per unit of time and volume of biofilter media (equation 2-9). The unit is defined as $g/m^3/h$ etc.

$$\text{Mass loading (surface)} = \frac{Q \times C_{gi}}{A \times V_1 \times 10^3} \qquad (2\text{-}8)$$

$$\text{Mass loading (volumetric)} = \frac{Q \times C_{gi}}{V_{bm} \times V_1 \times 10^3} \qquad (2\text{-}9)$$

Where: C_{gi} = inlet concentration (ppmv); Q = air flow (m^3/h); A = filter area (m^2); and V_{bm} = volume of filter bed media (m^3).

Elimination capacity of the biofilters can be equal to or less than the volumetric mass-loading rate. Under low loading conditions, the elimination capacity basically equals the load. The removal efficiency of the system is calculated to be at 100% (Figure 2.11). By increasing the mass-loading rate to a point where the overall mass-loading rate will exceed the overall EC, generating removal efficiency is less than 100 %. This point is typically called the critical EC. If the flow rate is increased or the volume decreased, the residence time is reduced. As a result, the contaminant may not have enough time to diffuse into the biofilm and be readily oxidized. Although biofilters are suitable for treating odours with low concentratins, they will operate under a wide range of load conditions. In general, the factors that are needed for interpreting the biofilters performance include C_{gi}, C_{go}, Q, V_{bm}, RE, and EC (Devinny et al., 1999). Moreover, Table 2.12 shows a summary of typical biofilter operating conditions.

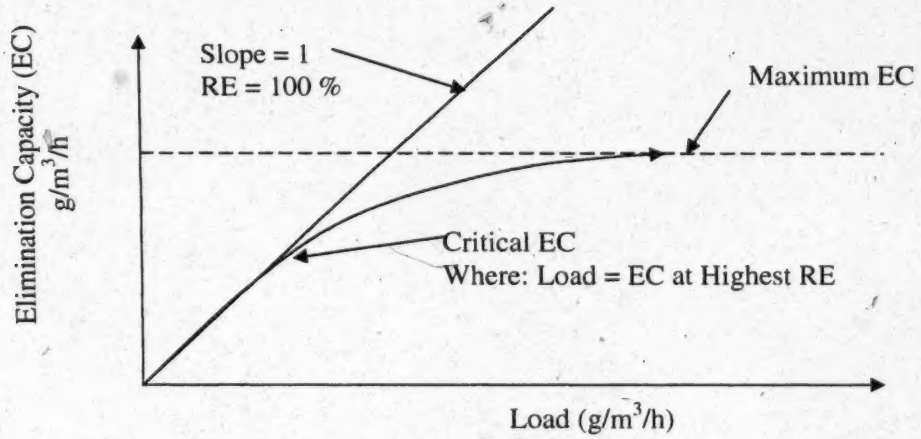


Figure 2.11 Typical elimination capacity (EC) vs. load curve (modified from Devinny et al., 1999)

Table 2.12 Typical biofilter operation conditions for treatment of air (adapted from Devinny et al., 199)

Parameter	Typical value
Biofilter layer height	1 to 1.5 m
Biofilter area	1 to 3000 m^2
Waste air flow	50 to 300,000 m^3/h
Biofilter surface loading	5 to 500 $m^3/m^2/h$
Biofilter volumetric loading	5 to 500 $m^3/m^3/h$
Bed void volume	50 %
EBRT	15 to 60 s
Pressure drop per meter of bed height	20 to 100 Pa (Max. 1000 Pa)
Inlet pollutant and / or odour concentration	0.01 to 5 g/m^3, 500 to 50,000 OU/m^3
Operating temperature	15 to 30°C
Inlet air relative humidity	>98%
Water content of the support material	60 % by mass
pH of the support material	6 to 8
Typical removal efficiencies	60 to 100%

2.2.2.9 A Biofilter for an Animal Facility

The rate of biodegradation of target compounds is described by the reaction kinetics of that system. Knowledge of kinetics is necessary to calculate the volume of the reactor needed to achieve the desired elimination of contaminants from a given waste air stream using a specific biofilter material (Coleman et al., 1995). Several researchers such as

Ottengraf and Driks (1992), Van Lith (1989), Sabo (1990), Ottengraf (1986), have published papers about the theoretical descriptions of the biofiltration processes. Essentially, modeling of the biofilters can be categorized into two types: steady state models and unsteady state or transient models.

The overall biodegradation rate in the biofiltration system is governed by the rate of diffusion of substrate to biomass (diffusion limited or diffusion dependent) and by the rate of substrate consumption by the biomass. This is reaction limited or reaction dependent (Tiwaree et al., 1992; Utgikar et al., 1991; Ottengraf and Diks, 1990; Ottengraf, 1987; Ottengraf and van den Over, 1983). When the inlet concentrations of target compounds are low, diffusion limitations exist. At higher concentrations, the system is reaction limited at a stable gas flow rate.

Selecting the right medium in terms of physical and chemical characteristics is central to the design and operation of a biofilter. The main factors that affect the design and operation of a biofilter are: type of target compounds, mass loading, temperature, airflow, elimination capacity (EC), removal efficiency (RE), EBRT, pH, water application to maintain moisture content of media, production of by-products such as nitrite, nitrate, sulphate, and capital, as well as operational costs. However, the most important parameters for an efficient biofilter are medium pH, moisture content, bed temperature, nutrients, contaminant load, and controlling by-products.

The existence of more than 300 odourants in animal facilities, notably hog barns, makes modeling of biofilters complicated. However, the main target odourants in the animal facilities are volatile fatty acids (VFAs), amine family such as NH_3, and sulfide family such as H_2S. Quantitatively, the dominant odourants by mass in barns are NH_3 and H_2S. Based on the theory of biofiltration, there is no concern about the biodegradation of target compounds such as fatty acids because, with proper EBRT, the end products should be CO_2 and H_2O. Nitrifying bacteria (*Nitrosomonas* sp. and *Nitrobacter* sp.), with an optimum pH value of 7 to 8, are effective in NH_3 biooxidation. The optimum range of pH values for microorganisms responsible for biooxidation of H_2S (*Thiobasillus* sp.) is 2 to 4. The end products of NH_3 and H_2S biooxidation are nitrate and sulphate, respectively. The accumulation of these end products can decrease the pH of biofilter medium to acidic levels that are not suitable for the nitrifying bacteria. However, if the amount of NH_3

entering surpasses the capacity of a biofilter's ammonia degradation ability, the excess NH_3 is expected to dissolve in the water producing ammonium that can increase the pH value of the biofilter medium to basic conditions. If a biofilter is operated under farm conditions with the presence of NH_3 and H_2S, the media used has good physical and chemical characteristics and other operational factors, such as moisture content, pressure drop, nutrients, etc., are at optimum levels, there still remain two issues. The first issue is the possible variation of pH, and the second is the accumulation of by-products, such as ammonia, ammonium, nitrite and nitrate, that can affect biofilter performance.

2.3 A Draft Mathematical Model to Predict Biofilter Operation

To address these issues, a draft mathematical model was developed to predict: a) mass of ammonia available in the contaminated air (g/d), b) elimination capacity (EC) ($g/m^3/d$), c) removal efficiency (RE) (%), d) production of nitrite and nitrate nitrogen (NO_2^--N and NO_3^--N) ($g/m^3/d$), e) pH of the leachate, f) amount of water needed for humidifying the contaminated air (m^3/d), g) amount of water required to control the concentration of nitrite and nitrate in the leachate, and h) empty bed retention time (EBRT) (s) (Appendix – A).

Before these factors can be predicted, data are required. Available data from the literature were included in the mathematical model. The input data to the mathematical model are tabulated in Table 2.13. The model was unable to predict the necessary output data from the model as shown in Table 2.14. There was insufficient literature data available to enable the model to predict the pH, EC, EBRT, and leachate required to prevent toxic NO_3^- and NO_2^- conditions. Also, the effects of temperature on biofilter performance also were lacking.

In order to predict biofilter performance based on NH_3 and H_2S loadings under a range of temperatures, data need to be collected from operating biofilters under field conditions at different concentrations of NH_3 and H_2S while measuring the operational factors. Assuming that NH_3 drives the nitrogen balance, different levels of NH_3 concentrations must be simulated. The data from these simulated trials will lead to a revised mathematical model that will be able predict reasonable values for outputs listed in Table 2.14.

Table 2.13 Input data to the draft mathematical model

Name of value	Symbol	Unit	Range
Available contaminated airflow	qs	L/s	0 to 3000
Temperature at the inlet of biofilter	t1	°C	0 to 35
Temperature at the outlet of biofilter	t2	°C	0 to 35
Average ammonia concentration of the polluted air	c1	ppm	0 to 90
Average inlet hydrogen sulfide concentration	ss1	ppm	0 to 1
Average outlet hydrogen sulfide concentration	ss2	ppm	-------
Relative humidity of the air at the inlet	rh1	%	0 to 100
Relative humidity of the air at the outlet	rh2	%	0 to 100
Days of operation after14 days of start up	d1	day	0 to 360
Amperage of one of the water pump	Ip	ampere	0 to 15
Voltage used for one of the pump	vp	volt	0 to 220
Number of pumps (pumps are the same)	np	---	0 to 10
Amperage of one of the fans	Iff	ampere	0 to 15
Voltage of one of the fans	vff	volt	0 to 220
Number of fans (fans are the same)	nf	---	0 to 20
Time that fans are working per day	timf	hour	0 to 24
Price of electricity/kwh	pe	CN $	0 to 0.11
Price of water/gallon	pw	CN $	0 to 0.11
Price of media/m^3	pm	CN $	0 to 40

Table 2.14 Output data from the draft mathematical model

Name of values	Symbol	Predicted Values	Unit
Mass of ammonia in the pilot scale experiment	cgi	0.00	g/d
Mass of ammonia at the outlet of pilot scale	cgo	0.00	g/d
Elimination Capacity (EC)	EC	0.00	$g/m^3/d$
Elimination Capacity with effect of temperature	ECt	0.00	$g/m^3/d$
Predicted pH value	pH	0.00	-
Empty Bed Retention Time in pilot scale	EBRT	0.00	s
Predicted EBRT based on ECt	EBRT1	0.00	s
Predicted Removal Efficiency	RE	0.00	%
Predicted ammonia concentration at the outlet	C2	0.00	ppm
Mass of ammonia available in the polluted gas	cgit	0.00	g/d
Predicted volume of media based on ECt	V1	0.00	m^3
Temperature modification	a	0.00	
NH_3-N at the inlet air	y1	0.00	$g/m^3/d$
NH_3-N at the outlet air	y2	0.00	$g/m^3/d$
Prediction of NO_2^-- N production	y4	0.00	$g/m^3/d$
Prediction of NO_3^--N production	y5	0.00	$g/m^3/d$
Prediction of Volume of media based on total NO_2^-- N and NO_3^--N production	V2	0.00	m^3
Prediction of EBRT with V2 volume of media	EBRT2	0.00	s
Prediction of water needed for humidifier.	W	0.00	m^3/d
Prediction of water needed for chemical control.	Wa	0.00	m^3/d
Prediction of nitrite concentration with c1 ppmv NH_3 and effect of temperature through 36 days.	ya or yb or yc	0.00	ppm
Prediction of nitrate concentration with c1 ppm NH_3 and effect of temperature through 36 days	yd or ye or yf	0.00	ppm
Estimation of the cost of coarse compost media	Tcm	0.00	CN $
Estimation of the cost of electricity per day	TEP	0.00	CN $
Estimation of the cost of water per day	Tpw	0.00	CN $

2.4 References

American Society of Civil Engineers (ASCE). 1995. Odor control in wastewater treatment plants. Library of Congress Cataloging-in-Publication Data: USA.

ASTM E-758, 1991. Guidelines for Selection and Training of Sensory Panel Members. Philadelphia, PA.

ASTM E679-91, 1991. Standard Practice for Determination of Odor and Taste Threshold By a Forced-Choice Ascending Concentration Seies Method of Limits, American Society for Testing and materials, Philadelphia, PA.

Atlas, R. M. and Bartha, R. 1993. Microbial Ecology: Fundamentals and Applications (3rd edition). The Benjamin/Cummings Publishing Company, Inc. Redwood City, CA.

Biocycle. 1991. "The Biocycle Guide to the Art and Science of Composting" The JG Press, Inc., Emmaus, PA.

Bohn, H. L., and Bohn, R. K. 1986. Gas scrubbing by bio-washers and bio-filters. Pollut Eng, 18(6), 18-19.

Caunt, J., McNevin, D., and Barford. 1999. Chemical engineering in Australia. http://www.engaust.com.au/other/ceafresh.html July 5 2005.

Chan, W. and Zheng, R., 2005. A new synthetic biofiltration material: Poly (vinyl alcohol)/Pig manure compost composite beads. Journal of Chemical Technology and Biotechnology. 80(5): 574-580.

Chen, Y., J. Yin, K. Wang, S. Fang, 2004. Effects of periods of nonuse and fluctuating ammonia concentration on biofilter performance. Journal of Environmental science and Health Part-A,-Toxic/Hazardous Substances and Environmental Engineering. 39(9): 2447-2463.

Coleman, R. N., E.C. Dombroski, and R. Milner, 1995. Development and optimization of a modular biofilter for use as a sulphide process emission abatement technology for industry. Final Report. Microbiology Research & Development Alberta Environmental Centre and Milner Engineering, Vegreville, Alberta. (#23440-4-1025/01-SQ: DSS File #028SQ-23440-4-1025).

Corsi, R. and L. P. Seed. 1995. Biofiltration of BTEX: effects of media, multiple substrates, and dynamic mass loading Air and Waste Management Association, 88th Annual meeting and Exhibition, San Antonio, Texas, June 19-23.

Dawson, D.S. 1993. Biological treatment of gaseous emissions. Water Environment Research, Vol. 65, No. 6, p 368-371.52 ref.

Devinny, J.S. , 1989. Soil water content and air stripping, in Environmentatl Engineering. Proceedings of the 1989 Specialty Conference, American Society of Civil Engineers, U.S.A. New York, p. 555.

Devinny, J. S., M.A. Deshusses, and T.S. Webster, 1999. Biofiltration for air pollution control. Lewis Publishers, New York, USA.

Deshusses, M.A., and Cox, H.H.J., 2004. Biotrickling filters for air pollution control. Department of Chemical and Environmental engineering University of California Riverside, Ca 92521. mdeshuss@engr.ucr.edu.

Dravnieks, A., 1979. Odors from Stationary and Mobile Sources. Natl. Acad. Sci., Washington, D.C.

Dravnieks, A. and F. Jarke. 1980. "Odor Threshold Measurement by Dynamic Olfactometry: Significant Operational Variables." Journal of the Air Pollution Control Association, 30: 1284-1289.

Edwards, F. G. and Nirmalakhandan, N. 1996. Biological treatment of airstreams contaminated with VOCs: an overview. Water Science and tTechnology, 34: 565-571.

Eithner, D., 1984.Untersuchungen uber Einsatz und Leistungsfahigkeit von Konpostfilteration zur biologischen Abluftreining im Bereich van Klarangagen under besonderer Berucksichtigung der Standzeit. Investigations of the Use and Ability of Compost Filters for the Biological Waste Gas Purification with Special Emphasis on the Operation Time Aspects, GWA, Band 1, TWTH Aachen, West Germany.

Feddes, J. J. R., G. Qu, C. A. Ouellette, and J. J. Leonard. 2001. Development of an eight-panelist single port, forced-choice, dynamic dilution olfactometer. Canadian Biosystems Engineering 43: 6.1-6.5.

Filson, H., T. William, and E. Brendan, 1996. Natural and biological odour control methods for swine earthen manure storage areas. Pp.371-374. In:International Conference on Air Pollution from Agricultural Operations Conference Proceedings. Midwest Plan Service, Ames, IA.

Gesteland, R.C., et al. 1983. Physiological Processes in Olfactory Adaptation. Paper Presented at 76th Annu. Meeting Air Pollut. Control Assoc., Atlanta, Ga.

Gibons, M.J. and Loehr, R.C., 1998. Effect of media nitrogen concentration on biofilter performance. J. Air Waste Manage. Assoc., 48(3), 475.

Govind, R. 2001. (Unpublished paper) Biofiltration: An innovative technology for the future. University of Cincinnati, Department of Chemical Engineering, University Cincinnati, OH 45221-0171.

Hamilton, D. W. 2003. Lagoons for Livestock Waste Treatment. Oklahoma State University. http://www.agweb.okstate.edu/pearl/biosystems/general/f1736.htm. Feb 19, 2004.

Higgins, A., Chen, S., and Singley, M. 1982. Airflow resistance in sewage sludge composting aeration systems. Transactions the ASAE, 25(4), 1010-1018.

Keller, R. A., and Dyer, J. A. 1997. Halogenated VOC control technology selection. Presented at the Air & Waste Management Association's 90th Annual Meeting & Exhibition, June 8-13, Toronto, Ontario, Canada.

Kosteltz, A. M., Finkelstein, A., and Sears, G., 1996. What are the "real opportunities" in biological gas cleaning for North America, in Proceeding of the 89th Annual Meeting and Exhibition of the Air and Waste Management Association, Air and Waste Management Association, Pittsburgh, PA.

Leson, G. and A. M. Winer. 1991. Biofiltration: an innovative air pollution control technology for VOC emissions. Journal of Air Waste Management Association, 41(8), 1045-1054.

Martin, A. M., S.L. Nolen, P.S. Gess, and T.A. Baesen, December 1992. Control odours from CPI facilities. Chemical Engineering Progress, pp. 53-62.

McGinley, C. M. and D. L. McGinley, 1999. Diary of an odor Sample – Understanding odor Testing. Presented at the Virginia Water Environment Federation 1999 Education Seminar, Richmond, VA: November 4.

McGinley, C. M. Michael, A. and D. L. McGinley, 2000."Odour Basics", Understanding and Using Odour Testing. "Presented at the Annual Hawaii Water Environment Association Conference Honolulu, Hawaii: 6-7 June 2000.

Medina, V. F., T. Webster, M. Ramaratnam, and J. S. Devinny 1995. Treatment of gasoline residuals by granular activated carbon based biological filtration. Journal of Environmental Science and Health. A30: 407-422.

Menig, H., H. Krill, T. Jaeschke, T. Kosten, 1997. Effizienz biologischer Verfahren imVergleich zu anderen Abluftreinigungssystemen, in Biological Waste Gas Cleaning. Proceedings of an International Symposium, Prins. W.L. and van Ham, J., Eds., VDI Verlag GmbH, Duesseldorf, Germany, 1997, p. 27.

Metcalf and Eddy, Inc. 1991. Wastewater engineering: Treatment, disposal, and reuse (3rd edition). McGraw-Hill, Inc. New York. NY.

Metcalf & Eddy, 1993. Wastewater Engineering: Treatment, and reuse (4rd edition). McGraw-Hill, Inc. New York. NY.

Morgenroth, E., E.D. Schroder, D.P.Y. Change and K.M. Scow. 1995. Nutrient limitation in a compost biofilter degrading hexane. Paper 95-TP9C.05. 88th Air & Waste Management Association Annual Meeting and Exhibition, San Antonio, Texas, June 18-23,1995.

Moulton, D.G. (1974) Dynamics of Cell Populations in the Olfactory Epithelium. Ann. N.Y. Acad. Sci., 237,52.

Nicolai, R. E., and K. A. Janni. 1997. Development of a low cost biofilter for swine production facilities. Paper No. 97-4040. ASAE, St. Joseph, Mich.

Nicolai, R. E., and K.A. Janni, 1998. Comparison of biofilter retention time. Paper 984053. ASAE, St. Joseph, MI.

Nicolai, R.E., and K.A. Janni. 1999. Effect of biofilter retention time on emissions from dairy, swine, and poultry buildings. Paper No. 99-4149. ASAE, St. Joseph, Mich.

Noren, O. 1985. Design and use of biofilters for livestock building. In: Odour prevention and control of organic sludge and livestock farming, eds. V. C. Nielsen, J. H. Voorburg, and P. L'Hermite. Pp234-237. Elsevier Applied Science Publishers, New York.

O'Neill, D. H., Stewart, I. W., and Phillips, V. R. 1992. A review of the control of odour nuisance from livestock buildings: Part 2, the costs of odour abatement systems as predicted from ventilation requirements. J. Agric. Engng Res, 51, 157-165.

Ottengraf, S.P.P. and van den Oever, A.H.C. 1983. Kinetics of organic compound removal from waste gases with a biological filter. Biotechnol. Bioeng., 25: 3089-3102.

Ottengraf, S.P.P., 1986. Exhaust gas purification. In Biotechnology, Vol. 8 (eds. H.J. Rehm and G. Reed). VCH, Weinheim, FRG. Pp: 427-452.

Ottengraf, S.P.P., 1987. Biological systems for waste-gas elimination using scrubber, trickling filter or biofilter systems; xenobiotic degradation. Trends in Biotechnology 5 (5): 132-136.

Ottengraf, S.P.P., J.J.P. Meesters, A. H. C. van den Oever, and H.R. Rozema. 1986. Biological elimination of volatile xenobiotic compounds in biofilters for waste-gas waste-disposal, deodorization by filtration. Bioprocess Engineering 1 (2): 61-69.

Ottengraf, S.P.P., and R. Diks. 1990. Biological purification of waste-gases waste-gas treatment, deodourization and air purification using e. g. biofilter, scrubber and trickling filter. Chimicaoggi 8 (5): 41-45.

Paul, P.G., and C. Roos. 1989. Biological Waste Air Treatment with the Biobox. Proceedings of the 8th World Clean Air Congress 1989, W.C. Brasser, Ed. 399-404. The Netherlands, 11 September 1989.

Randa, M. B., Cooper, D. E., Woo, C. P., Fletcher, G. C., and Rolfe, K. A. 1991. Compost filters for H_2S removal from anaerobic digestion and rendering exhausts. Journal of the Air Pollution Control Association, 53(2), 185-189.

Sabo, F., 1990. Verfahremsteschnische Grundlagon der biologischen Ablufreiningung, in Biologische Aluftreiniggung; Expert Verlag, Ehningen, pp. 13.

Schiffman, S. S., J. L. Bnnett, J. H. 2001. Quantification of odors and odorants from swine operations in North Carolina. Agricultural and Forest Meteorology. 108: 213-240.

Shareefdeen, Z., Baltzis, B.C. 1994. Biofiltration of toluene vapor under steady state and transient conditions: theory and experimental results. Chemical engineering science, 49: 4347-4360.

Son, H.K., B.A. Striebig, R.W. 2001. Ethylbenzene removal in a multiple-stage biofilter. Journal of the Air and Waste Management Association (J. Air Waste Manage. Assoc.). Vol.51, no. 12: 1689-1695.

Son, H.K., B.A. Striebig, R.W. Regan, 2005. Nutrient limitations during the biofiltration of methyl isoamylketone. Environment Progress (Environ. Prog.). 24, 75-80.

Sorial, G.A., Smith, F.L.,Suidan, M.T.,Biswas, P., and Brenner, R.C., 1995. Evaluation of a trickle bed biofilter for toluene removal,. J. Air Waste Manage. Assoc., 45(12), 801.

Stevens, S.S., 1962. The surprising simplicity of sensory metrics. American Psychologist Journal, 17: 29-39.

Tiwaree, R.S., K. Cho, M. Hirai, and M. Shoda. 1992. Biological deodorization of dimethyl sulfide using different fabrics as the carriers of microorganisms. Appl. Biochem. Biotechnol. 32, 135-48.

Utgikar, V., R. Govind, Y. Shan, S. Safferman, and R.C. Brenner, 1991. Biodegradation of Volatile Organic Chemicals in a Biofilter. Emerging Technologies in Hazardous Waste Management II, D. W. F. G. Tedder, Chapter 12. Atlantic City, New Jersey, 4 June 1990. Washington, DC: American Chemical Society.

van Eyk, J., and C. Vreeken. 1991. In situ and on-site subsoil and aquifer restoration at a retail gasoline station. In: In Situ Bioreclamation. R.E. Hinchee and R.F. Olfenbuttel (eds). Butterworth-Heinemann. Boston, MA. pp, 303-320.

Vanlith, C., 1989. Design Criteria for Biofilters. Presented at the 82nd Annual Meeting of A & WMA, Anaheim, CA. June 25-30.

Vansickle, J. 1999. Biofilters provide low-cost odour solution. National Hog Farmer, June 1999. 12-13.

Weber, F. J and Hartmans, S. 1995. Use of activated carbon as a buffer in biofiltration of waste gases with fluctuating concentrations of toluene. Appl. Microbiol. Biotechnol., 43(2), 365.

Werner, W., H. G. Liebe, and B. Striefler. 1986. Emission Control with Biofilters: Application, Design and Operational Experience. Seventh World Clean Air Congress, 537-544. Sydney, Australia, 25 August 1986.

Williams, T. O., and Miller, F. C. October 1992. Odour control using biofilters. BioCycle, 73-77.

Yang, Y. and Allen, E.R., 1994. Biofiltration control of hydrogen sulfide 1: design and operational parameters. J. Air Waste Manage. Assoc., 44(7), 863.

Zhang, R. H., D. L. Day, L. L. Christianson, W. P. Jepson, 1993. A computer model for predicting ammonia release rates from swine manure pits. Silsoe Research Institute. UK.

Zhu, J., Bundy, D. S., Li, X., and Rashid, N. 1997. Swine manure odor control using pit additives-A re w. In proceedings of the fifth international symposium, Livestock environment. ASAE. MI: USA.

3. RESEARCH OBJECTIVES AND SCOPE

For many years, researchers have tried to identify the major causes of malodours from swine manure. More than 330 odourants have been reported in swine barns and most of them have odour detection thresholds lower than or equal to 0.001mg/m^3. Six of the 10 compounds with the lowest odour detection thresholds contain sulphur. Although ammonia was thought to be useful as an indicator for malodour, due to its relatively high concentrations and the easy determination, it was proved to be a poor factor in evaluating odour intensities (Lunn and van De Vyver, 1977). Ammonia detection threshold is reported as 17 ppm meanwhile the detection threshold of hydrogen sulfide is 0.0005 ppm (ASCE, 1995).

The major odourous materials include: volatile fatty acids (VFAs), the sulfide family (Hydrogen sulfide, Mercaptan, Dimethyl sulfide, Dimethyl disulfide), and the amine family (Ammonia, Methyl amine, Dimethyl amine, Chloro-amine) (Chapter 2).

Quantitatively, the most important the odourants in swine barns include ammonia (53%), trimethylamine (14%), dimethylamine (12%), hydrogen sulfide (12%), fatty acids (5%), and phenols and indoles (0.4%). Moreover, these compounds have been classified as highly biodegradable materials (Chapter 2).

As mentioned earlier (Chapter 2) biofilters have the greatest potential for cost-effective operation to treat moderate gas flows containing low concentrations of contaminants.

Normally there are two types of operations for biofilters (Figure 3.1):

1- Low load operation or ideal operation (Load $\leq$ EC), with a stationary water phase, and a steady-state microbial ecosystem where nutrient content would be maintained and continually recycled. Degradation of the biomass releases the nutrients in soluble form where they can be taken up again by growing cells (Figure 3.1). However, biofilters produce leachate, either intentionally or inadvertently, an d this will remove dissolved nutrients out of the biofilter.

2- High load operation (Load $\geq$ EC) with growing biomass and possibility of issues such as by-product accumulation, clogging, and lack of nutrients in the biofilter media. The lack of nutrients will happen because with high load operation the biomass grows rapidly and may tie up all the nutrients. Gibbons and Loehr (1998) determined that the highest treatment rates in a compost-perlite biofilter were partially limited by soluble nitrogen

availability unless the concentration was 1000 mg/kg of wet bulk compost-perlite media, and that the nitrogen-to-carbon ratio should be at least 1 to 100.

In animal facilities such as pig barns, there is the potential of high concentrations of ammonia, hydrogen sulfide, and other odourous contaminants. Therefore, to use biofiltration technology in these facilities efficiently, the focus should be on high-load operation.

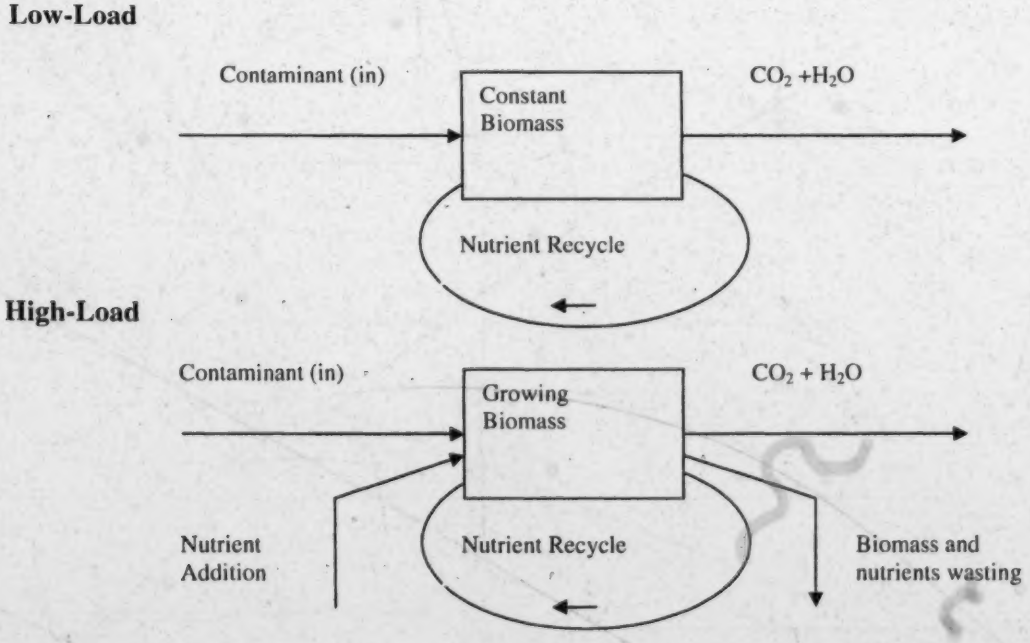


Figure 3.1 Comparison of two types of biofilter operation (modified from Devinny et al., 1999)

Our preliminary biofiltration experiments in a swine facility using different materials such as peat moss, polystyrene, wood chips, mixes of them (with and without nutrients), and coarse compost showed that coarse compost is more effective in terms of biofiltration efficiency. These experiments showed that water application is essential for biofiltration. Also, the wide variety and high concentrations of odourous gases, notably hydrogen sulfide and ammonia, and dust in the biofiters are the important factors that affect biofilter operations. With the assumption that ammonia and sulfur compounds (notably hydrogen sulfide) are quantitatively the dominant odorants in the barn, there is a big gap of information about the effect of the combination of those gases on the biofilter

performance. This research will be conducted in the swine facility of the University of Alberta to fill the gap of information and to provide data needed for revising the prediction Model (Appendix - A).

3.1 Objectives:

The objectives of this study were:

1. To determine the effects of NH_3 and H_2S concentration in the treatment plant of a swine facility on a biofiltration system (combination of biotrickling and compost biofilter).
2. To evaluate the effects of sulfuric acid on the elimination capacity and overall odour reduction of the above systems for NH_3, and H_2S.
3. To assess the performance of the above system using contaminated air from inside the barn with high concentrations of NH_3 and low concentrations of H_2S by measurement of the important operational factors (Chapter 2) that are necessary for revising the predictive model (Appendix-A).
4. To evaluate the effect of ammonia on biofilter operational factors such as pH, EC, RE and odour reduction in swine facilities.
5. To evaluate the influence of NH_3 concentration (0, 20, 45, and 90 ppmv) on the nitrogen mass balance and nitrification process in biofilters.
6. To improve a predictive model and suggest an improved biofilter design and operation for application in swine facilities.

In order to achieve the outlined objectives, this study was conducted in three experiments:

1. Preliminary experiment
2. Biofilter and Bioscrubber combination using dilute sulfuric acid scrubber
3. Ammonia injection to the biofilters for:

    Evaluating the effect of ammonia on performance and removal efficiency of a biofilter

    Evaluating water application in a biofilter used to treat exhaust air from swine facilities.

    Modeling nitrogen mass balance in biofilters

3.2 References

American Society of Civil Engineers (ASCE). 1995. Odour control in wastewater treatment plants. Library of Congress Cataloging-in-Publication Data: USA.

Devinny, J. S., Deshusses, M.A., and Webster, T. S. 1999. Biofilteration for air pollution control. Lewis Publishers, New York, USA.

Gibbons, M.J. and Loehr, R.C., 1998. Effect of media nitrogen concentration on biofilter performance. J. Air Waste Manage. Assoc., 48(3) 475.

Lunn, F., and J. van De Vyver. 1977. Sampling and Analysis of Air in Pig Houses. Agriculture and Environment. 3: 159-169.

4. PRELIMINARY EXPERIMENT

4.1 Introduction

Various factors influence biofilter operation. Moisture content within the biofilter is one of the most critical operational parameters that must be controlled to maintain optimal filter performance. Variation in the moisture content within the filter has been shown to be the largest single factor contributing to poor odour removal performance (Williams and Miller 1992). Numerous materials, such as peat, compost, activated carbon, woodchips, perlite, soil, sand, synthetic materials like polystyrene, shredded bark, heather, volcanic ash, or a mixture of these materials, can be used as biofilter media. The filter material on which the microorganisms are immobilized has to allow easy passage of moisture and effluent gases and also has to provide good conditions for microbial growth (Hong and Park 2005; Williams and Miller 1992). Peat moss has proved to be an excellent material because it possesses a high surface area per unit mass and a high water retention capacity. Thus, it provides good living conditions for the microorganisms. It is also inexpensive and easily available (Yang and Allen 1994; Williams and Miller 1992). The support material should have suitable properties for bacterial attachment. Research has indicated that microorganisms are more readily colonized on the surface of rough, porous, and hydrophilic media (Durham et al. 1994). However, compaction, clogging (biomass accumulation due to high loads and abundance of nutrients), and channelling are very common during biofilter operation. Choosing media with good physical and chemical characteristics is essential to providing optimum conditions for the microorganisms' growth and the long-term stability of the biofilter performance. However, the choice of biofilter material depends on many physical and chemical factors of the contaminated air such as: the contaminant type and concentration level, temperature, relative humidity, and intended flow rates. Moreover, the cost and life of the material affect the economics of the biofiltration system.

In this preliminary experiment, two biofilters treated air with high levels of ammonia and hydrogen sulfide from the manure treatment plant at the University of Alberta swine facility. Different media, such as coarse peat moss, polystyrene, a mixture of peat moss and polystyrene, woodchips, and compost, were used.

4.2 Objectives

The objectives of the study were:

a) To operate the biofilters with a mixture of the peat moss (25% by volume) and polystyrene (75% by volume) while monitoring the operational factors such as water application, leachate, moisture content of the media, pH, pressure drop, and airflow.

b) To evaluate the odour removal efficiency of two pilot-scale biofilters by measuring odour concentration and hedonic tone at the inlet and outlet of the biofilters.

c) To determine the effect of temperature and supplemental nutrients on the performance of the two pilot-scale biofilters.

4.3 Materials and Method

Two biofilters were made available from the Alberta Research Council in Vegreville (Figures 4.1, 4.2, and 4.3). Each biofilter consisted of a vertical tank made of acid-resistant fibreglass, with a diameter of 1.22 m, height of 1.83 m, and volume of 1890 L. A plastic grate with 25 mm openings and covered with two layers of 13 mm plastic mesh was used to support the biofilter material and to create a 0.30 m high air inlet plenum at the bottom of each tank. The top of each biofilter was closed with a removable, vented fibreglass lid. The biofilters, as well as the air ducts and outside water lines, were insulated to prevent heat loss and avoid freezing of the water lines during cold winter temperatures.

Each biofilter was filled with 1000 L of medium, resulting in a filter bed 1 m deep with a 0.50 m headspace.

Figure 4.1 Two biofilters used for the preliminary experiments

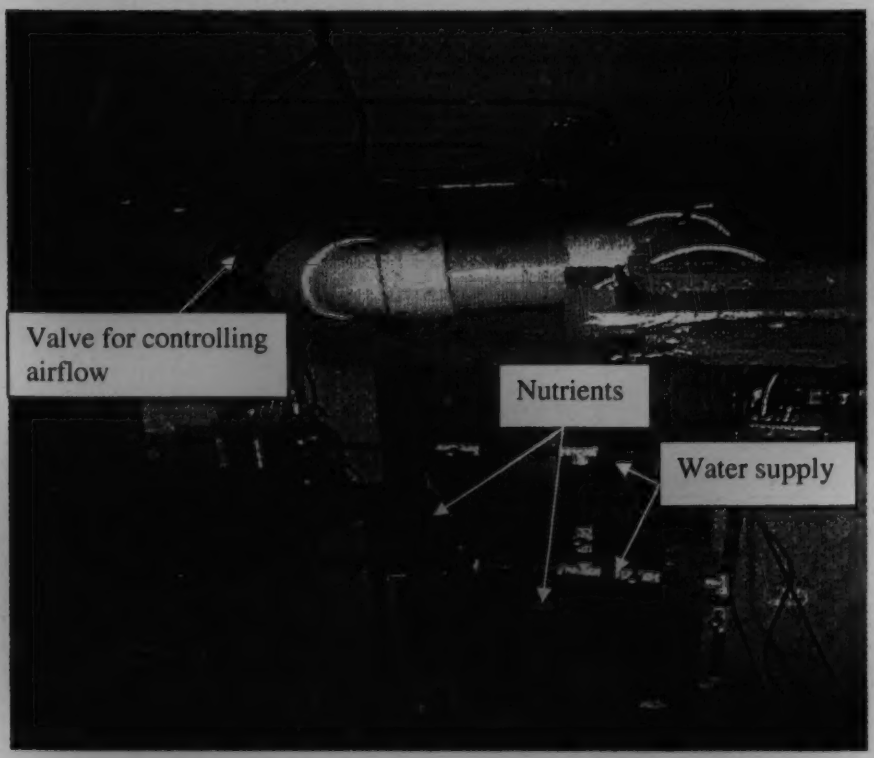


Figure 4.2 Instrumentation for water application, temperature, and nutrient control

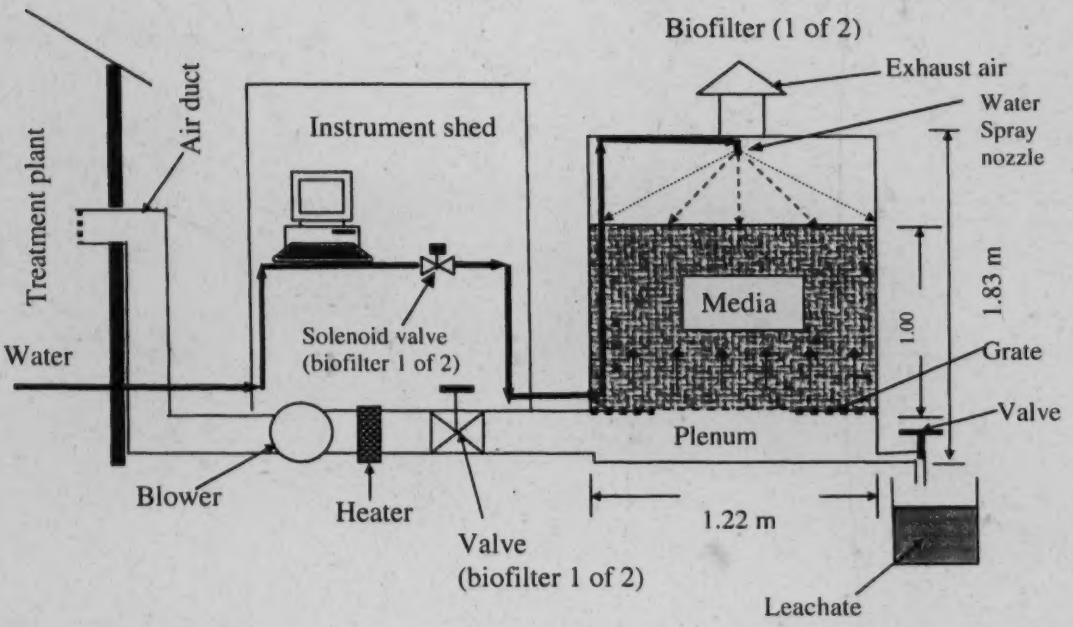


Figure 4.3 Schematic diagram of pilot-scale biofilters, instrument shed, and treatment plant

4.3.1 Airflow

The objective in designing an air distribution system is to transfer contaminated air from the source to the biofilter for homogeneous distribution through the filter media. The treatment plant of the swine facility at the University of Alberta was selected as a source of odours because it generated a continuous supply of odours with approximately consistent intensity and character. The contaminated air was drawn from above the primary settling manure tank in the treatment plant of the swine facility. The blower used to transfer the air (Model 4C329, Dayton Electric Manufacturing Co., Chicago, IL) was capable of delivering 200 L/s and was powered by a 2.24 kW industrial motor (Model M3158T, Baldor Electric Co., Fort Smith, AR). From the blower, the contaminated air was split and channelled to the two biofilters through 0.15 m diameter PVC ducts. The ducts extended 2 m into the air intake plenums of the biofilters (Figure 4.3).

The airflow rate was monitored by pressure gages (Magnehelic Model 2000-00C, Dwyer Instruments Inc., Michigan City, IN) connected to pitot tubes in the ducts. These measured velocity pressure from which airflow rate was determined (Appendix-B). Since

some of the preliminary experiments were conducted during the winter, condensation in the pitot tubes located in the instrument shed caused the gages to malfunction. Therefore, a hotwire anemometer (VelociCalc Model 8350, TSI Inc., St.Paul, MN) was used to measure air velocity at weekly intervals. The average velocity each time measured at 7 locations in vertical and 7 locations in horizontal lines.

The pressure drop across each biofilter was monitored using Magnehelic pressure gages (Model 2010C, Dwyer Instruments Inc., Michigan City, IN), and condensation was not a problem in this case. Static pressure upstream of the filter media was measured using pressure taps in the fibreglass tank wall.

4.3.2 Water Application

City water was sprayed on the surface of the filter material using a wide-angle spray nozzle mounted 0.30 m above the filter bed. To improve the application of water, 7.35 m long, 13 mm diameter perforated hose was installed. The hose was laid in a spiral within the filter medium at a depth of 0.50 m. A ball valve was manually adjusted to split the flow between the spray nozzle and the perforated hose when setting up for each new experiment. The relative humidity (RH) of the contaminated air was measured at the inlet and outlet of the biofilters using a psychrometer (Psychro-Dial Model CP-147, Environmental Tectonics Corp., Southampton, PA). Water application to each biofilter was controlled with a programmable timer (Model 1507, Noma Consumer Electrical, Canada) and a solenoid-activated valve applied water to the biofilters twice a day for one minute per application. The mean water flow rate to each biofilter was measured with flow meters (Model RMC-144 S 20K, Dwyer, Instruments Inc., Michigan City, IN). An outlet valve was located at the bottom of each biofilter so that water could be drained from the air inlet plenum. The water in the biofilter plenum was drained and its volume recorded daily. The bed depth decreased 5 to 10%.

4.3.3 Nutrients

Peat moss has much less nutrient than compost. Therefore, adding supplemental nutrients may be required. Synthetic media, such as polystyrene, do not contain nutrients or microorganisms. They must be added. However, during operation of a biofilter, nutrients

may be lost by leachate or sequestered into the biomass. Because there is no release of nutrients from the media, similar to what occurs with slowly decomposing compost, they must be resupplied by continuous or occasional addition to the irrigation water. However, the control of water and nutrient supply depend on the specific nutrient requirements, water absorption capacity of the media, and the need to control and wash out by-products (Devinny et al. 1999). In the preliminary experiments for testing the peat moss or polystyrene, microorganisms were added by inoculation (20 L activated sludge was manually sprayed on the surface of each biofilter's materials), and supplement nutrients were added to both biofilters. The activated sludge provided from ARC Vegreville sprayed on the media before starting the operation of them. The nutrients were dissolved in 4 L water and injected into the added water at an adjusted dilution so that the following amounts were applied weekly: 3 g of KH_2PO_4, 1 g of NH_4Cl, 0.21 g of $MgCl_2$, and 0.12 g of $CaCl_2$. These amounts were determined on the basis of previous work with nutrient-poor filter material (Coleman et al. 1995). The chosen nutrients do not react with one another.

In the experiments with mixtures of peat moss and polystyrene, nutrients were added to one biofilter material to better support the growth of various *Thiobacillus* spp., a genus of autotrophic bacteria that is mainly effective in oxidising reduced sulfur compounds such as hydrogen sulfide, mercaptans, some thiols, and other organic sulfides (Buchanan and Gibbons 1974). These sulfur-containing compounds are strong odourants with low odour threshold, and so it is important that a biofilter has an optimum support for growing the mentioned microorganisms. The supplemental nutrients were injected into the water stream of one of the two biofilters with an applicator (Model DPG2VJ-F, Dosmatic U.S.A. International Inc., Carrollton, TX). The other biofilter did not receive supplemental nutrients. Nutrient application began on the fifth day of each trial because previous experience had shown that it took about five days of operation for the filter media to become wet.

4.3.4 Evaluation of Biofilter Performace for Odour and Gas Removal

Air samples were collected in 10-L Tedlar sampling bags (Cat. No. 232-08, SKC Gulf Coast Inc., Houston, TX) on days 14, 21, and 28. Air samples (two bags per sample) were

taken from the inlet duct, and the two biofilter exhaust vents. When heaters were used for preheating the contaminated air, two more samples were taken after using the 6 kW heater. This procedure was repeated three times to give a total of nine samples. Each sub-sample was analyzed for odour concentration and hedonic tone using a dynamic olfactometer at the University of Alberta (Feddes et al., 2001). A sampling pump (Matheson-Kitagawa Model 8014-400A, Matheson Tri-Gas, Parsippany, NJ) and the appropriate detector tubes were also used to measure ammonia concentration (Ammonia 2/a, Dräger; range 0 to 20 ppm with accuracy ±5%) and hydrogen sulfide was measured by using the Toxi Ultra instrument, S/n G24155. Before using this instrument, it should be calibrated with the hydrogen sulfide in the cylinder (5 ppm) and fresh air (0 ppm). The accuracy of thses instrument was ±10%.

4.3.5 pH

The pH of the application and drainage water from each biofilter was measured at weekly intervals using an electronic pH meter (Digi-Sense Model 5985-80, Cole Parmer Instrument Co., Chicago, IL).

4.4 Biofilter Materials

Peat moss is naturally a hydrophobic medium with acidic characteristics and does not contain a large population of microorganisms. Thus, inoculation with activated sludge is required. Peat moss has much less nutrient content than compost and thus may require the addition of nutrients. Peat moss was widely used as a medium in the 1980s because it offered a very low-pressure drop (Devinny et al., 1999). For biofilters to become practical in animal facilities, notably pig barns, the pressure drop would need to be very low - 20 to 100 Pa (Devinny et al., 1999) to minimize power and equipment requirements. In this study, two types of material were used: peat moss (Sunshine Select Canadian Sphagnum, SunGroHorticulture Canada Ltd., Edmonton, AB) and polystyrene figures 4.4, 4.5, and 4.6. Six packages (each package compressed to 107 L) of the coarse peat moss were used in each biofilter. After opening the packages, the total volume increased. After spraying water, decreased to about 1 m^3.

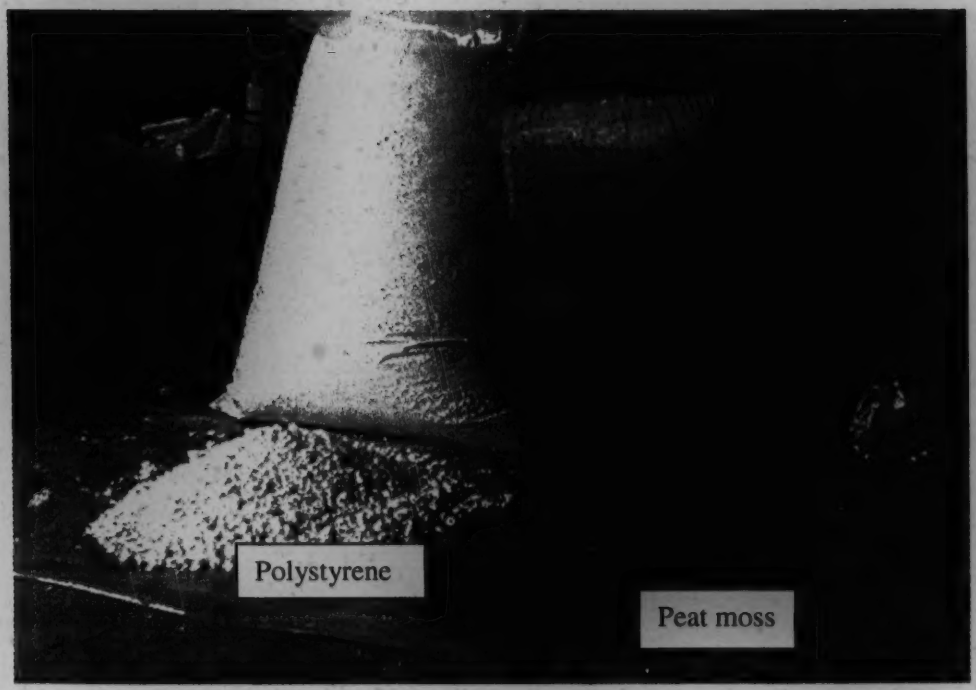


Figure 4.4 The coarse peat moss and shredded polystyrene that were tested in the preliminary experiment as the biofiilter media

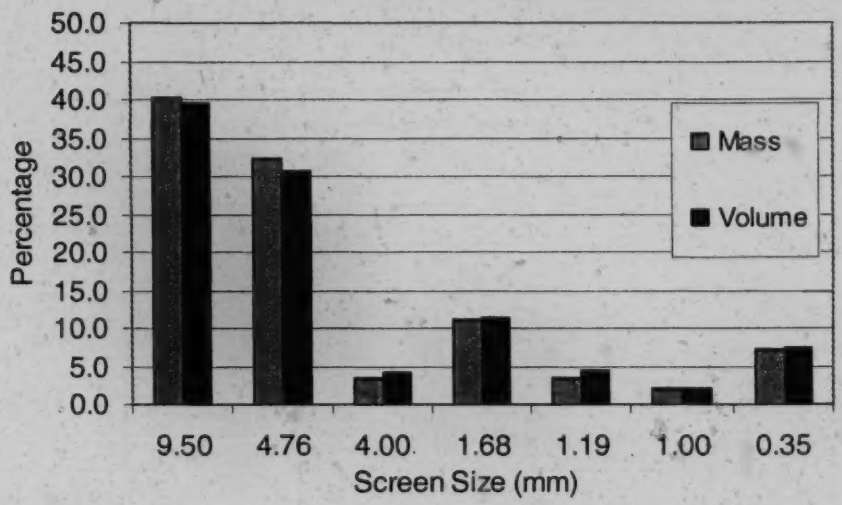


Figure 4.5 Peat moss particle size distribution used in the preliminary experiments

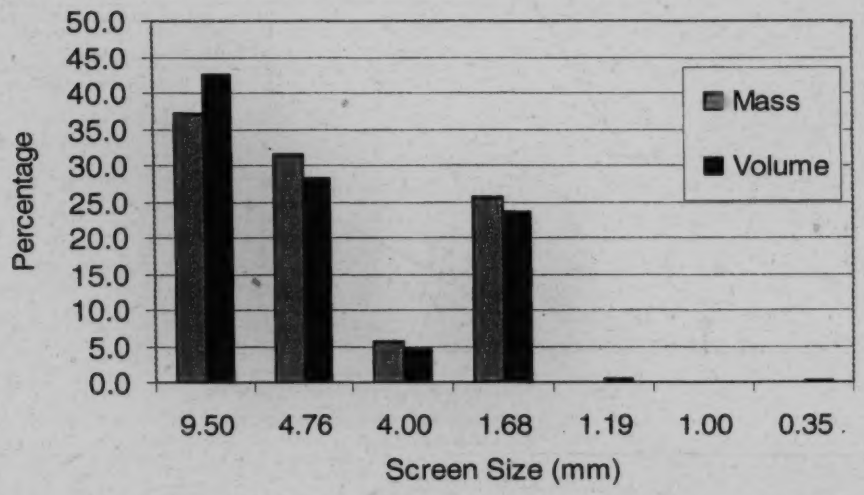


Figure 4.6 Polystyrene particle size distribution that was used in the preliminary experiments

4.4.1 Preliminary Test

The measurement of the pressure drop and airflow of the contaminated air are the basic physical factors for testing the biofilter media. Two biofilters operated with peat moss and 10s EBRT. However, the above factors were monitored (see appendix-B for details), and olfactometry of the odour samples conducted biweekly. In another test, one of the biofilters operated with polystyrene. The pressure drop was stable (40 to 50 Pa) when the biofilter was operated with 10s EBRT. Table 4.1 shows the results of these tests. Based on advantages and disadvantages of the above materials (Table 4.2), a mixture of three parts of crumbled polystyrene and one part of peat moss (by volume) was used as the biofilter media (Figure 4.7).

Table 4.1 Comparison of the pressure drop, airflow, and odour removal of the biofilters using peat moss and polystyrene

Biofilter media	Pressure drop (Pa)	Airflow (L/s)	Odour removal (%)	Applied water ($L/m^3/d$)
Peat moss	1163 ± 534	89 ± 37	44	10
Polystyrene	40 ±10	100±10	20	10

Table 4.2 The important advantages and disadvantages of using peat moss and polystyrene as the biofilter media

Media	Advantages	Disadvantages
Peat moss	1. High surface area 2. Having some source of nutrients 3. Good absorbability of water 4. Good odour reduction (44%)	1. High pressure drop 1163±534 Pa/m under wet condition 2. Chance of compaction and channelling 3. High operating cost due to the high-pressure drop
Polystyrene	1. Very low pressure drop 40 to 50 Pa/m 2. Low chance of compaction 3. Low energy is needed for operating the biofilter	1. Very low water holding capacity 2. Low odour reduction (20%) if it is used alone as the biofilter medium

Figure 4.7 The mixture of three parts crumbled polystyrene and one part peat moss (by volume) that was used as the biofilter media

This experiment was conducted with three replications and two treatments, including air

temperature (15, 22.5, and 30°C) and nutrients (adding supplemental nutrients and no additional nutrients).

4.6 Results

The daily water application to each biofilter was calculated (more details will be discussed in chapter 7) based on the set-point temperature, wet and dry bulb temperatures in the treatment plant and the mean nozzle application rate.

The volume of the water application required depends highly on the temperature and relative humidity of the polluted air. The amount of water applied to the biofilters every half-hour was based on a daily calculation of water needed. For example: if the daily water application was calculated at 40 L for a biofilter every half-hour, 0.8 L water applied to that biofilter. The relative humidity of the air at the outlet of the biofilters remained stable throughout the experiment (77.8±5.4%). However, Table 4.3 shows the results of the measurement of the volume of applied water and leachate for each treatment. Moreover, Table 4.4 shows the averages and overall averages of the moisture content of the media throughout the experiment.

Table 4.3 The overall averages of the water application and leachate in the biofilters were operated with three temperatures (Clark et al. 2004)

	Treatments			Overall
	15°C	22.5°C	30°C	
Applied water: Ave ± SD ($L/m^3/d$)	33.1±12.1	93.1±10.8	153.8±20.4	101.3±48.9
Leachate: Ave ± SD ($L/m^3/d$)	13.7±11.9	26.0±12.0	33.9±32.9	25.0±23.7

Table 4.4 Moisture content of the media for different depth and temperature (Clark et al. 2004)

Temp (°C)	Rep	Top Ave±SD (% w.b.)	Middle Ave±SD (% w.b.)	Bottom Ave±SD (% w.b.)	All depths Ave±SD (% w.b.)
15	1	-	-	-	-
15	2	63±34	50±36	72±24	60±34
15	3	60±29	67±21	77±5	68±22
15	All	62±31	59±30	75±15	64±28
22.5	1	46±37	63±34	70±29	60±34
22.5	2	65±25	79±6	81±3	75±16
22.5	3	51±27	62±27	45±29	53±28
22.5	All	54±30	68±26	65±28	62±29
30	1	23±23	48±33	56±28	42±32
30	2	74±18	78±4	68±17	73±15
30	3	65±21	69±14	71±8	68±15
30	All	55±31	66±22	65±20	62±25
All	All	56±30	65±26	67±23	63±27

In biofiter systems, many factors affect the pH values, such as type of odourants at the inlet (notably ammonia or hydrogen sulphide), their by-products, water application, and volume of the leachate. However, due to the possible variation of the pH of the biofilter medium at top, middle, and bottom of the media, the pH of the leachate of the biofilters were measured in this experiment. The concentrations of the above gases in the treatment plant were measured with the ranges of 0 to 20 ppm and 1 to18 ppm for hydrogen sulfide and ammonia, respectively. There were high variations in the pH values of the leachate of the biofilters throughout the experiment. The overall pH of the leachate of the biofilter with supplemental nutrients decreased slightly from 7.6±0.2 to 7.1±0.7 and 7±1.3 (Figure 4.8). The overall pH of the leachate of the biofilter with no nutrients was decreased slightly from 7±0.5 to acidic conditions 6.7±1.4 (Figure 4.9). However, the minimum and maximum of the pH of the leachate of the biofilter with supplemental nutrients were 3.2 and 8.5, respectively. Moreover, the minimum and maximum of the pH of the biofilter without nutrients were measured 2.7 and 8.5, respectively. This is important because the nitrification processes cease at low pH (lower than 6) (Metcalf and Eddy, 1993). The reason for the variation of the pH values was not clear. The concentration of the by-products was not monitored. However, more research is needed to evaluate the by-

products and their relation to the odourants at the inlet of the biofilter.

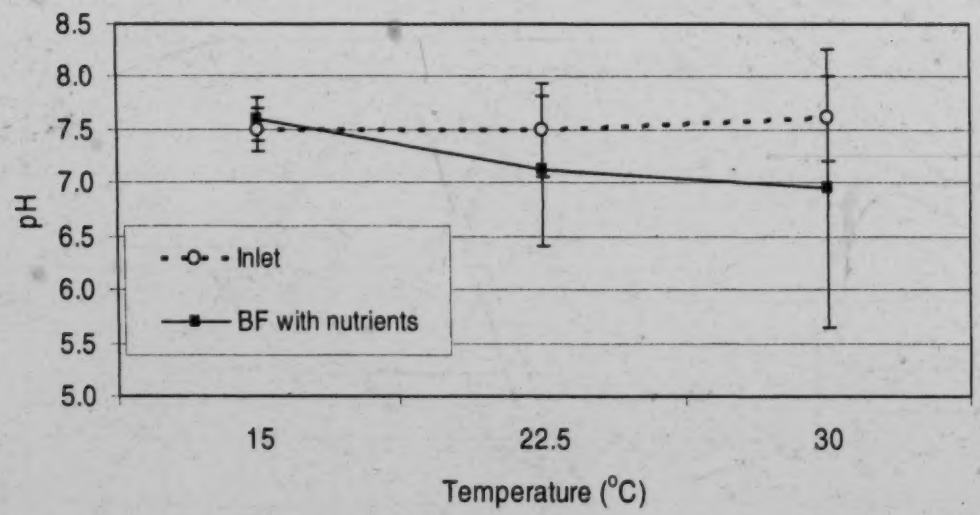


Figure 4.8 Variation of pH of the applied water and leachate of the biofilters with supplemental nutrients

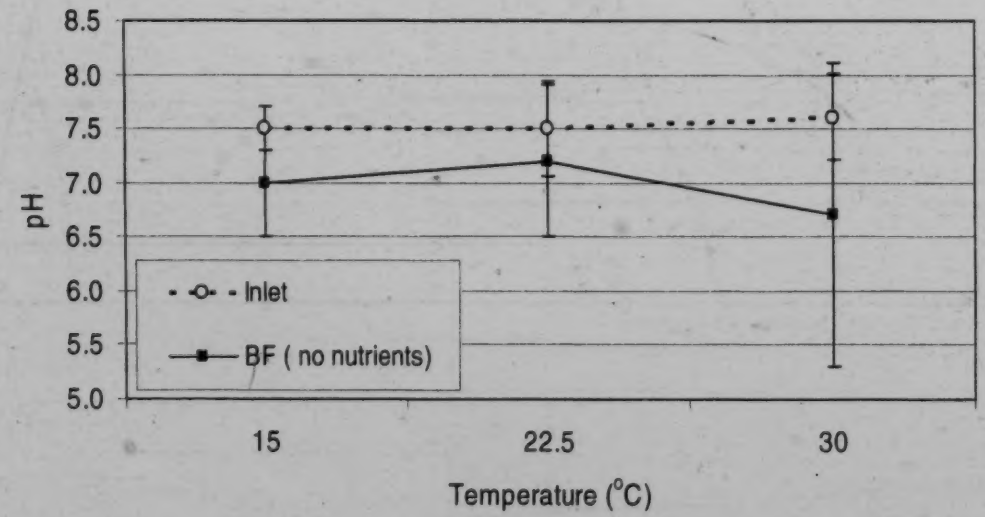


Figure 4.9 Variation of pH of the applied water and leachate of the biofilters with no supplemental nutrients

The olfactometry results of this experiment are summarized in Table 4.5. Statistically, there was no significant difference between the biofilters with and without nutrient

application for odour reduction (p=0.05). Biofilter 1, operated at 15°C with nutrient application, reduced the odour concentrations by 37, 39, and 67% for days 14, 21, and 28, respectively. The odour removal efficiency of this biofilter through 28 days of operation increased from 37 to 67%, and at the same time, the hedonic tone improved from 21 to 27%. Biofilter 2, operated at 15°C, reduced the odour concentrations by 35, 20, and 67% for days 14, 21, and 28, respectively. The hedonic tone was improved for the above days by 21, 27, and 0%, respectively. At higher temperatures (22.5 and 30°C), an increase in biofilter effectiveness for odour reduction was expected, but this did not occur. The biofilters on day 21 of operation at 22.5°C increased the odour concentrations. However, at day 28, the odour was reduced marginally by 1 to 12%. On day 28, the biofilters with 30°C just reduced odour concentration by 2 to 18%. At the end of each trial, the pressure drop increased to about 250 Pa. and a slight clogging or compaction was observed at the bottom of the media (Figure 4.10).

Table 4.5 Mean odour concentrations (DT), hedonic tone (HT) and net change by biofilters (BF1 and BF2) for different temperature treatments

15°C	**Day 14**			**Day21**			**Day 28**		
Location	Inlet	BF1	BF2	Inlet	BF1	BF2	Inlet	BF1	BF2
DT (OU_E/m^3)	361	226	234	404	245	323	313	102	103
HT	-3.3	-2.6	-2.6	-3.1	-2.4	-2.3	-3.2	-2.4	-3.2
Change DT (%)		-37	-35		-39	-20		-67	-67
Change HT (%)		21	21		23	27		27	0
22.5°C									
DT (OU_E/m^3)	228	148	135	331	502	349	355	314	354
HT	-2.6	-2.2	-2.3	-2.8	-2.3	-2.6	-2.9	-2.7	-2.9
Change DT (%)		-35	-41		+52	+5		-11	-1
Change HT (%)		+15	+15		+17	+7		+7	0
30°C									
DT (OU_E/m^3)	206	101	102	212	86	103	241	198	237
HT	-2.8	-2.2	-2.1	-3.2	-2.8	-2.9	-3	-2.7	-2.7
Change DT (%)		-51	-50		-59	-51		-18	-2
Change HT (%)		+22	+25		+13	+9		+10	+12

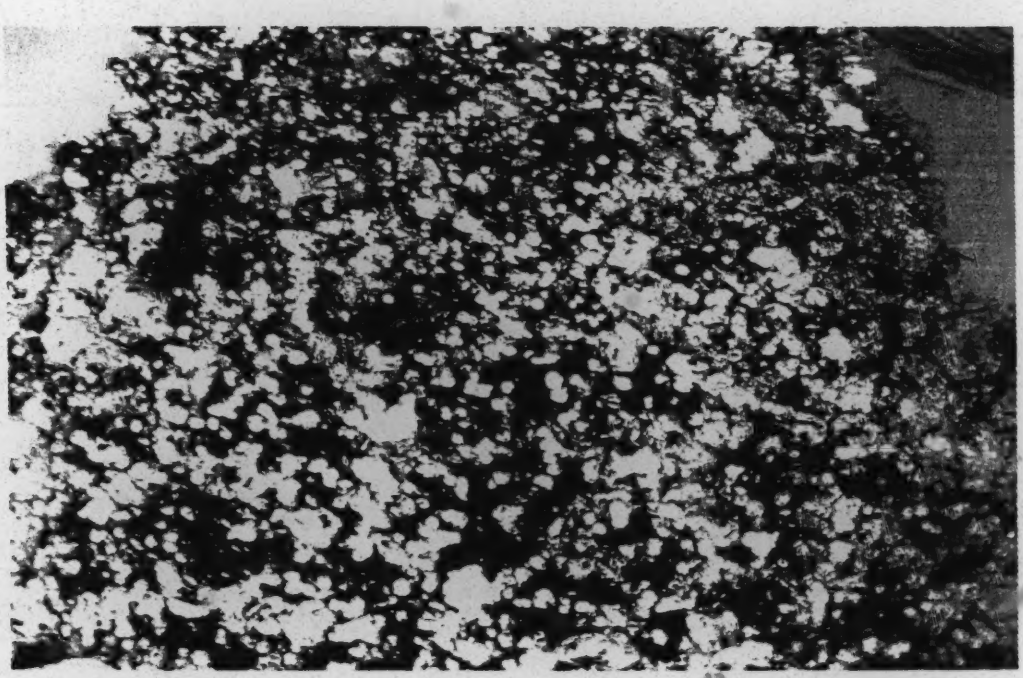


Figure 4.10 The picture of biofilters' media after 28 days of operation (some oily materials were produced at the bottom of the media that caused a slight clogging and increase the pressure drop)

4.5 Conclusions

1. A mixture of polystyrene (75% by volume) and peat moss (25% by volume) provided the best performance for biofilter.

2. The results of the experiment with the above mixture were extremely variable.

3. The minimum and maximum pH values of the leachate of the biofilters were in the range of 3 to 8.5, which is not a good indicator of good biofilter performance.

4. The highest odour removal efficiency was observed at 15°C (67%), and the lowest removal efficiency was measured at inlet temperatures of 22.5 and 30°C (8±8%).

5. The highest improvement of the hedonic tone was measured at 15°C (27%), and the lowest at 22.5 and 30°C (7%).

6. Temperature had no apparent influence on odour removal ($p=0.05$).

7. The addition of nutrients did result in an apparent increase of odour removal (from 38 to 45%), but this change was not statistically significant.

8. For good biofilter performance, water application is essential.

4. 6 References

Buchanan, R.E. and N.E. Gibbons (eds.). 1974. Bergey's Manual of Determinative Bacteriology. 8th edition. Baltimore, MD: Williams and Wilkens.

Clark, O.G., I. Edeogu, J. Feddes, R.N. Coleman and A. Abolghasemi.2004. Effects of operating temperature and supplemental nutrients in a pilot-scale agricultural biofilter. Canadian Biosystems Engineering. 46: 6.7-6.16.

Coleman, R.N., E.C. Dombroski and R. Milner. 1995. Development and Optimisation of a Modular Biofilter for Use as a Sulphide Process Emission Abatement Technology for Industry. Final Report: Contract # 23440-4-1025/01-SQ; Dss File #028SQ-23440-4-1025. Devon, AB: CANMET Energy Technology Center, Natural Resources Canada.

Devinny, J.S., M.A. Deshusses and T.S. Webster. 1999. Biofiltration for Air Pollution Control. Boca Raton, FL: Lewis.

Durham, D.R., Marshall, L.C. Miller, J.G. and Chmurny, A.B., 1994. Characterization of inorganic biocarriers that moderate system upsets during fixed- film biotreatment processes. Appl. Environ. Microbial., 60 (9), 3329.

Feddes, J.J.R., G. Qu, C.A. Ouellette and J.J. Leonard. 2001. Development of an eight-panelist single port, forced-choice, dynamic dilution olfactometer. Canadian Biosystems Engineering 43: 6.1-6.5.

Hong, J.H. and Park, K.J. 2005. Compost biofiltration of ammonia gas from bin composting. Bioresource Technology (Bioresour. Technol.). Vol. 96. no. 6, 741-745.

Metcalf and Eddy, Inc.1993. Wastewater engineering: Treatment, and reuse. (4rd Edition). Revised by: G. Tchobanoglous, F.L. Burton, and H.D. Stensel, McGraw-Hill, Inc. New York. NY.

Williams, T. D. and Miller, F. C. (1992). Biofilters and facility operations. Biocycle, 33, 75-79.

Yang, Y. and E.R. Allen. 1994. Biofiltration control of hydrogen sulphide: Design and operation parameters. Air &Waste Management, 44: 863-868.

5. EXPERIMENT 1: COMBINATION OF BIOFILTER AND BIOSCRUBBER USING DILUTE SULFURIC ACID

5.1 Introduction

As mentioned in Chapter 2, biofiltration is most effective for dilute contaminated gas streams. When the inlet concentrations of odourants increases, the required biofilter volume will need to increase to achieve a given removal efficiency. Consequently, at extremely high VOC concentrations, biofiltration becomes less feasible and other air pollution control techniques, such as absorbtion, adsorption, incineration, etc., provide more economically attractive solutions (Devinny et al., 1999).

Because the degradation of a VOC depends upon many different parameters, no single value can be considered as the upper limit for a compound concentration for biofilters. However, Leson and Winer (1991) suggest that the inlet VOC concentrations should not exceed 3,000 to 5,000 mg/m^3, and Yavorsky (1993) recommend 2,500 mg/m^3 of VOCs as a maximum level of the gas concentration that can be easily biodegraded. On the other hand, Hodge et al.(1992) report that chlorinated organic compounds and other slowly biodegradable compounds are degraded more slowly. Consequently, the maximum concentration is relatively lower.

High concentrations of an odourant or a sudden increase in concentration can adversely affect microbial populations. Biomass accumulates in a biofilter with reasonable loads, and when mineral nutrients are abundant, clogging may occur. Media clogging causes large pressure drops and encourages air channeling. Backpressures on the blower equipment increase detention time, increase wear on the system, and raise electrical demand. Air channeling will limit the amount of contaminant being treated and will negatively affect the performance of a biofilter (Devinny et al., 1999).

Under aerobic conditions, many species of microorganisms can oxidize hydrogen sulfide to produce sulfuric acid at a high conversion rate. Thus, biofiltration is an effective treatment process for this gas. However, the acid produced causes the pH of the biofilter to drop, and some investigators have seen substantial reductions in treatment success (Yang and Allen, 1994). This is often countered by the addition of buffering materials to the medium or by the addition of base with the irrigation water. An alternative is to allow the biofilter to operate at low pH. A series of species of genus *Thiobacillus* is capable of

oxidizing hydrogen sulfide successfully in environments with low pH (Atlas and Bartha, 1993; Islander et al., 1991; Metcalf and Eddy, 1991). Below pH 3, systems are often dominated by *Thiobacillus thiooxidans*, which oxidizes sulfide rapidly. *T. thiooxidans* is not inhibited until the pH falls below 1. The range of pH values for which *T. thiooxidans* can survive is reported to be 1 to 6, with the optimum pH of 2.0 to 2.8 (Atlas and Bartha, 1993). Another contaminant that can produce acidic condition is NH_3. This is oxidized as shown by equation 5-1.

$$NH_3 + 2O_2 \longrightarrow H^+ + NO_3^- + H_2O \qquad (5\text{-}1)$$

The process of oxidation of NH_3 is called nitrification. Nitrifying bacteria are chemolithotrophs that use energy produced by nitrification to assimilate CO_2. In the first reaction of nitrification, ammonia or ammonium will be reduced to nitrite by *nitrosomonas*. In the second step, nitrite is oxidized to nitrate by *nitrobacter*. The optimum range of pH values for the above bacteria is about 7 to 8.5 (Atlas and Bartha, 1993). There is no problem operating biofilters with low pH when the primary odourant is H_2S because sulfur-oxidizing bacteria, particularly *Thiobacillus* species, prefer extremely acidic conditions. If other odourants are presented, however, their removal efficiency will be adversely affected by the low pH. When a diversity of compounds is present in the waste gases, low pH conditions will adversely effect total odour removal. Therefore, monitoring of pH and maintenance in the general range of 7 to 8.5 is recommended for biofilters. However, if the concentration of NH_3 is high in the waste gases there is a possibility of high pH as shown by equation 5-2.

$$NH_3 + H_2O \longleftrightarrow NH4^+ + OH^- \qquad (5\text{-}2)$$

There is the potential of ammonia and hydrogen sulfide emission from stored manure. Depending on the concentration of these gases, there is the possibility of having low pH values resulting from the multi-step process of nitrification and the oxidation of hydrogen sulfide.

It is therefore desirable to try to reduce or treat one of the dominant compounds, such as NH_3 or H_2S, before biofiltration. A number of techniques are available for this including absorption, adsorption, and oxidation (thermal, chemical, and biological). Water is the most common solvent for wet scrubbing and may be combined with other chemicals to increase absorption or remove gases that are absorbed. The most common chemicals that

can be used in the wet scrubbing process include:

Oxidizing agents such as hydrogen peroxide (H_2O_2), sodium hypochlorite (NaOCL), and potassium permanganate ($KMnO_4$).

Sulfuric acid (H_2SO_4) and Hydrochloric acid (HCl).

Basic compounds such as lime (CaO), hydrated lime ($Ca(OH)_2$), and caustic (NaOH) (Haug, 1993).

In this experiment, dilute sulfuric acid was used to neutralize the dissolved ammonia, which would otherwise raise the solution pH and reduce further mass transfer. The end product of the combination of sulfuric acid and ammonia is ammonium sulfate $(NH_4)_2SO_4$, which can be used as a fertilizer. Also, sulfuric acid can change the pH of the bioscrubber liquid to an acidic environment that is good for growth of *Thiobacillus* spp. and degradation of H_2S. The rationales for adding bioscrubber to biofilter are that bioscrubber provides saturated air to biofilter, can remove NH_3 by adding sulfuric acid, and may remove odour.

5.2 Objectives

1) To measure the concentrations of ammonia and hydrogen sulfide available in the inlet air from the treatment plant and from the outlet of bioscrubbers and biofilters.

2) To determine the effects of NH_3 and H_2S concentration existing in the manure treatment plant air on the bioscrubber compost biofilter combination.

3) To evaluate the effects of using dilution of sulfuric acid (0.02%) on removal efficiency of bioscrubber for NH_3, H_2S and overall odour reduction.

5.3 Materials and Methods

Two bioscrubbers and two biofilters (Figures 5.1 and 5.2) has been constructed to treat exhaust air from the manure treatment plant of the swine facility at the Edmonton Research Station, University of Alberta. Each biofilter has a cylindrical shape made of plastic material, with a diameter of 0.56 m, height of 1.20 m, and total volume of 300 L. The top of each biofilter is covered by a wooden lid, which can be removed for servicing. To prevent the compaction of the materials in the biofilters, each biofilter is designed with three layers (0.25 m of material in each layer) and 0.10 m of empty space between

the layers. Painted metal mesh with a size of 5mm was used in each layer and a 0.30 m air inlet plenum was created at the bottom of each biofilter. On each layer, 50 L of coarse compost screened with a 20 mm screen, the material left over the screen is used as biofilter media. However, a total of 150 L medium was used for each biofilter.

Each bioscrubber has a cylindrical shape made of plastic material with a diameter of 0.56 m, a height of 1.15 m, and a total volume of 280 L. By installing a layer of plastic screen at a height of 0.60 m from the bottom, each bioscrubber is divided into two spaces, with the bottom space of about 95 L volume used as a reservoir to circulate scrubber water, and the top utilized for material placement. For having better control on the temperature, both bioscrubbers are located in a wooden box with size $1.55 \times 0.70 \times 0.65$ m divided into two equal spaces.

Three types of material (Figure 5.3) were used in the bioscrubbers. Thirty litres of expanded polystyrene (Beaver Plastics Ltd., Edmonton, AB) form a layer at the bottom of the bioscrubber media (first layer). Then, 50 L of mixed crumbled polystyrene (Beaver Plastics Ltd., Edmonton, AB) and perlite with a size over 3mm (50% by volume polystyrene and 50% of perlite) were used to form another layer over the above layer.

Another important operational factor measured included temperature in 7 locations (source, inlet and outlet of bioscrubbers, and outlet of biofilters).

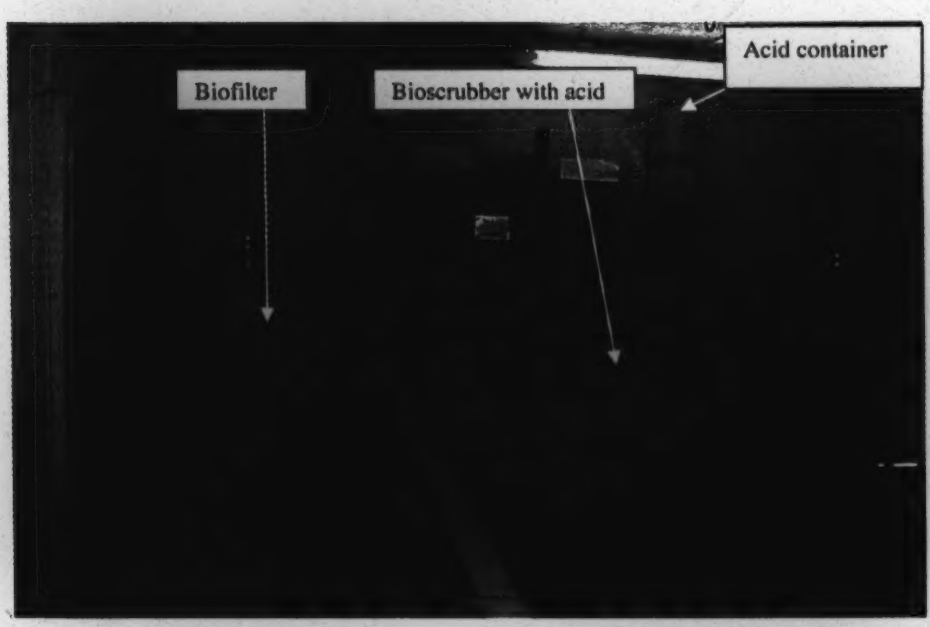


Figure 5.1 Combination of scrubber and biofilter for using dilute sulfuric acid

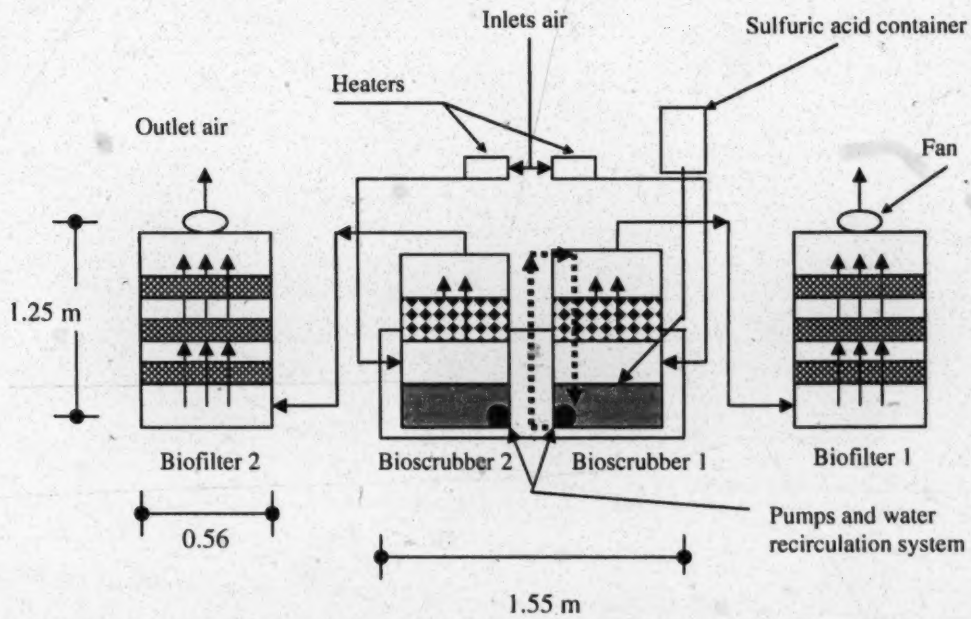


Figure 5.2 Schematic diagram of combination of bioscrubbers and biofilters. Dilute sulfuric acid was used in the Bioscrubber 1

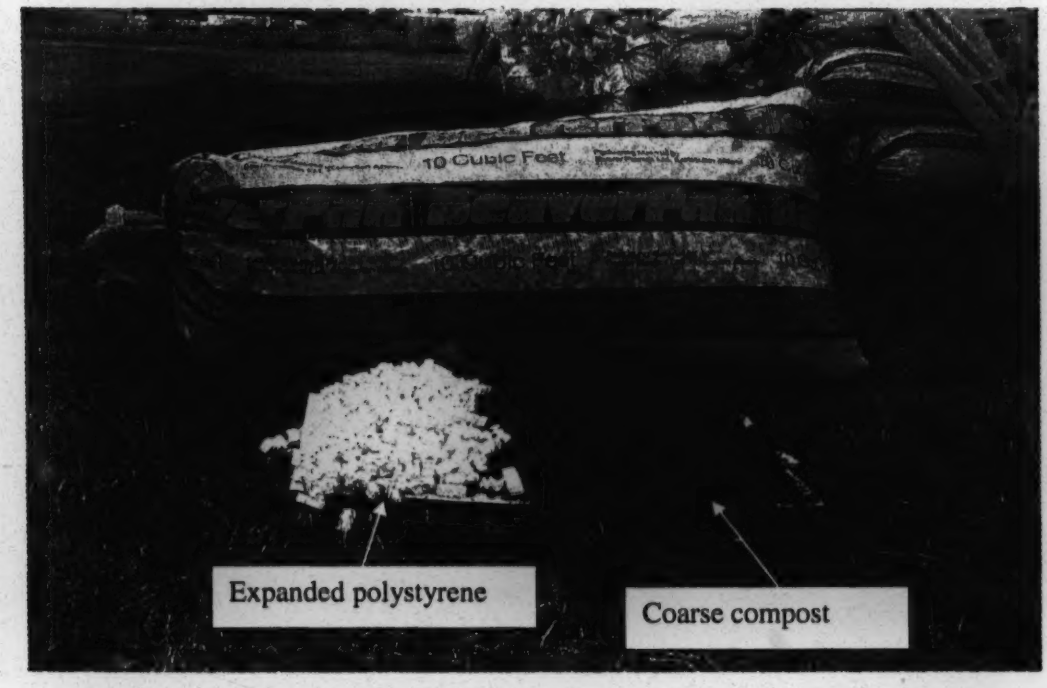


Figure 5.3 Expanded polystyrene was used in bioscrubbers and coarse compost was used in the biofilters

The concentrations of ammonia and hydrogen sulfide were measured at five locations (inlet of bioscrubber, outlets of bioscrubbers, and outlets of biofilters) five days per week. A sampling pump and the appropriate detector tubes were used to measure ammonia (Matheson-Kitagawa Model 18014-400A, Matheson Tri-Gas, Pasippany, NJ). Hydrogen sulfide was measured by using the Toxi Ultra instrument, S/n G24155. Before using this instrument, it should be calibrated with the hydrogen sulfide in cylinder (5 ppm) and fresh air 0 ppm (A small pump Gilian BDXII Abatement was used to provide 1L/min airflow for the instrument).

Odour samples were collected in Tedlar sampling bags (Cat. No. 232-08, SKC Gulf Coast Inc Houston, TX) at the end of weeks 2, 4, and 6 from six locations (Inlet and outlet of each bioscrubber, outlet of biofilters). Each sample comprised two sub-samples (i. e., two sample bags), giving a total of 12 sub-samples. The sub samples were analyzed for odour concentration and hedonic tone using an eight-port, forced-choice olfactometer at the University of Alberta (Feddes et al., 2001).

5.4 Water Application

A small submersible pump (PCL-010 Little Giant, OK) was installed in the bottom of each scrubber. The flow rate of the circulating water of each scrubber was measured (10±1 L/min). The total volume of circulating water for each bioscrubber was 90 L. In order to replace the amount of water that each bioscrubber lost due to evaporation, a float valve was installed inside each scrubber to maintain the water level. The average amount of water used in each bioscrubber was 4.5 ± 0.5 L/day.

City water was applied to each biofilter from a tap via a soaker hose, 8 m of which was spiraled throughout the three layers of each biofilter. All the amount of water was not sprayed on the top of the media because it can wash out the microorganisms and nutrients from the bottom layer. A programmable timer (Noma Consume Electrical Model 1507, made in Canada) with a solenoid activated valve applied water to the biofilters twice a day for one minute per application. The flow rate from the soaker hoses was approximately between 0.8L/min or 1.6L /day because the timer was on for two minutes.

5.5 Air Conditioning

The treatment plant air was preheated during cold weather. Two 1500 W, portable fan-forced convection heaters (Model FH2000, Super Electric Co, Markham, ON) were installed in the air intake area of the bioscrubbers. Each heater was regulated at 1000 W and preheated the air continuously while a rheostat and thermostat controlled the heater operation and temperature.

Air velocity was measured with a velocity meter (VelociCalc Model 8350, TSI Inc., St. Paul, MN) after the biofilters. On the top of each biofilter a fan was installed for providing: upward flowing air in the bioscrubber and biofilters. Weekly air velocity after the biofilters was measured at seven vertical locations and seven horizontal locations. The average was used as the air velocity of each system. However, the airflow through each bioscrubber was maintained at about 20±2 L/s. As a result, the empty bed residence time (EBRT) of each bioscrubber was about 5 s. The pressure drop across each scrubber was monitored using a manometer (Dwyer Mark II); it varied from 22 to 30 Pa. The pH of the bioscrubbers' circulating water and biofilters' leachate was measured at five-day intervals using an electronic pH meter (Digi - Sense Model 5985-80, Cole Parmer Instrument Co.,

Chicago, IL).

5.6 Sulfuric Acid Solution

Pure sulfuric acid (99%) (20 ml) was dissolved in 4L of tap water daily and a glass valve was used to drop the solution in the bioscrubber 1 to provide a dilution of 0.02% of sulfuric acid all at once. However, because the volume of the liquid of the bioscrubber was constant (95 L) and 20 ml of acid was added during 24h, the actual concentration of the acid in the bioscrubber liquid was expected much lower than 0.02% because the amount of acid gradually added to the bioscrubber daily.

The amount of sulfuric acid is needed can be calculated as follow:

The first step is calculating the quantitative amount of ammonia based on the volume of daily available contaminated air, temperature, and concentration of ammonia. The following formula shows how the mass of ammonia can be calculated:

$$V_1 = \frac{mRT}{P} \times \frac{28.32}{17 \times 453} = \frac{(1)(0.730)(492 + 1.8T_1)}{(1)(272.12)} \qquad (5\text{-}3)$$

Where:

V_1 = the volume for 1 g of gas at temperature T_1 (°C) of contaminated air (L)

m = 1(g)

P = 1 atmospheric pressure

R = 0.730 (the universal gas constant)

$T1$ = temperature of the contaminated air (°C)

T = absolute temperature, = 492 + 1.8 $T1$ (gas temperature) (Haug, 1993)

To determine the volume of the polluted air with measurement of the airflow:

$$\text{Total mass of ammonia that daily enters in the biofilter (g)} = \frac{V \times C}{10^6 \times V_1} \qquad (5\text{-}4)$$

Where:

V = Volume of polluted air per day (L/d) = $60 \times 60 \times 24 \times Q = 8.64 \times 10^4 \times Q$

Q = average airflow pass through the biofilter (L/s)

C = ammonia concentration (ppmv)

The absorption and neutralization reactions between ammonia and sulfuric acid are:

$$2NH_{3g} \longleftrightarrow 2NH_{3aq} \qquad \text{(absorption)} \qquad (5\text{-}5)$$

$$2NH_{3aq} + 2H_2O \longleftrightarrow 2NH_4^+ + 2OH^- \quad \text{(ionization)} \qquad (5\text{-}6)$$

$$2H^+ + SO_4^= + 2OH^- \longleftrightarrow 2H_2O + SO_4^= \quad \text{(neutralization)} \qquad (5\text{-}7)$$

$$2NH_{3g} + 2H^+ + SO_4^= \longleftrightarrow 2NH_4^+ + SO_4^= \quad \text{(net)} \qquad (5\text{-}8)$$

The molecular weight of H_2SO_4 is 2(1) + (32) +4(16) = 98.

The required quantity of sulfuric acid is calculated from the following equation:

Mass of needed sulfuric acid based on 20 L/s airflow = $\frac{98 \times NH_3(g/d)}{2 \times 17}$ (Haug, 1993)

See an example of the estimation of sulfuric acid and mass of ammonia in Appendix –C.

5.7 Results

A summary of the measurements of some operational parameters is shown in the Table 5.1.

Table 5.1 Overall averages of some operational factors

Airflow L/s (Ave.±Sd)	Circulation water (L/min)	Leachate of BF1 (L/d)	Leachate of BF2 (L/d)	Moisture of Media (%) (Ave.±Sd.)	Relative Humidity (%)	
					Intake air (Ave.±Sd.)	Outlet of scrubbers
20 ± 2	10±0.5	1.6±0.3	1.1±0.2	64±4.3	71±8.6	>95

The stable moisture content of biofilter media was expected with adding bioscrubber to the biofiter. However, at the end of each trial, a total of nine samples from the top, middle, and bottom of the biofilter were provided. After weighting the samples, They were put in the oven at 70 °C for 48h. Again, each sample was weighed and moisture content calculated. The overall moisture content was 64±4.3% of wb.

Figure 5.4 shows the temperature at the above locations with the standard deviation from the means. Heaters increased the intake air temperature on the averages from 19.1±1.5 to 27.7±1.6 and 26.5°C±1.4 for the bioscrubber 1 and bioscrubber 2, respectively. The heaters increased the air intake temperature about 7 to 8°C. The temperatures of the air decreased through the bioscrubber 1 and 2 from 27.7°C±1.6 and 26.5°C±1.4°C to

19.7°C±1.1 and 19.6°C±1.1, respectively. This is due to evaporations. The mean air temperatures at the inlets to the bifilter 1 and 2 were 19.7±1.2 and 19.6°C ±1.1. The outlet temperatures for these biofilters were 19.6°C±1.2 and 19.6°C±1.1. The temperatures of the circulating water of the bioscrubbers were 19.4°C ±1.6 and 19.2°C±1.8 for bioscrubber 1 and 2, respectively.

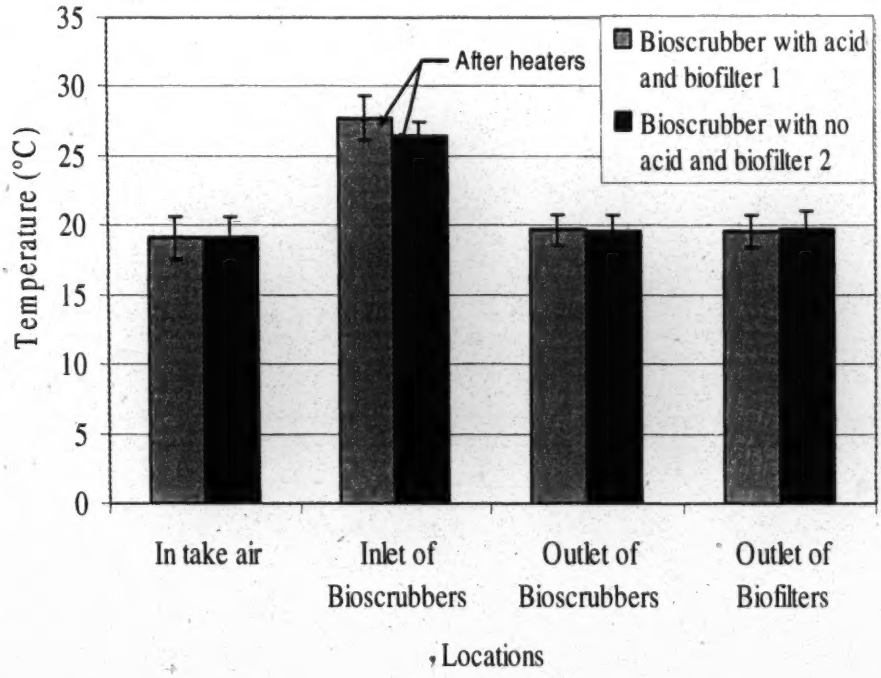


Figure 5.4 Overall averages of air temperature change through the combination of bioscrubber and biofilter

The pressures at four locations (outlet of scrubbers, outlet of biofilters) were measured. The results are shown in Figure 5.5. As mentioned earlier, the pressure drop for the mixture of peat moss (25% by volume) and expanded polystyrene (75% by volume) was 200 to 600 Pa. The pressure drops of 20 Pa through the bioscrubber and about 65 Pa for the combination of bioscrubber and biofilter is a good level of pressure drop for the media.

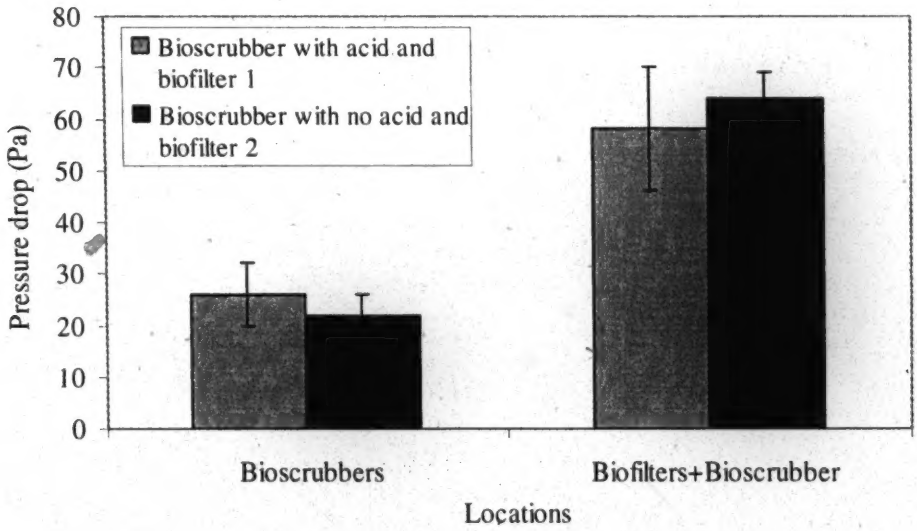


Figure 5.5 Overall pressure drops through two biofiltration systems (combination of bioscrubber and biofilter)

5.7.1 Measurements of pH

A preliminary test was conducted to evaluate the effect on pH of adding sulfuric acid to tap water as a source of water for the scrubbers. For this test, 0.1 ml sulfuric acid was added to 4 L of tap water. Then, after shaking for two minutes, the pH of the solution was recorded. Gradually, the concentration of sulfuric acid was increased up to 1.2 ml, and the pH was recorded. The pH of the tap water decreased from 8.5 to 3.5. Figure 5.6 shows how the addition of sulfuric acid linearly changed the pH of the liquid. After starting the experiment, the pH of bioscrubbers liquid, and biofilters leachate were measured five days a week throughout the experiment (Digi - Sence Model 5985 - 80, Cole Parmer Instrument Co., Chicago, IL). Figure 5.7 shows the pH of the bioscrubbers through the experiment. The average pH values of the liquid in bioscrubbers 1 and 2 were 6.6±1 and 7.1±0.6, respectively. There are two reasons that the variation of the pH in the bioscrubber 1 (with acid) was higher than the other bioscrubber: 1) it was difficult to adjust dropping 4 L of sulfuric acid solution for 24 hours, and 2) the variation of the ammonia concentrations in the treatment plant.

For getting an idea about the microbial populations, at the end of the experiment eight samples provided from the bioscrubbers and biofilters media and sent to the Alberta

Research Council (ARC) in Vegreville for microbiological analysis. The result (Appendix-D) showed that the biofilters and bioscrubbers media with lower pH had the higher number of *Thiobacillus* spp. responsible for eliminating H_2S.

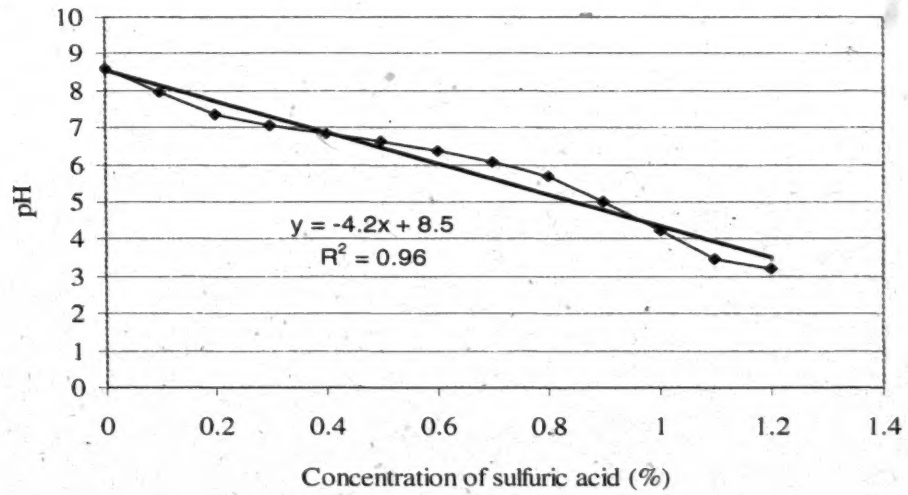


Figure 5.6 pH of the solution of tap water and sulfuric acid vs. the concentration of sulfuric acid

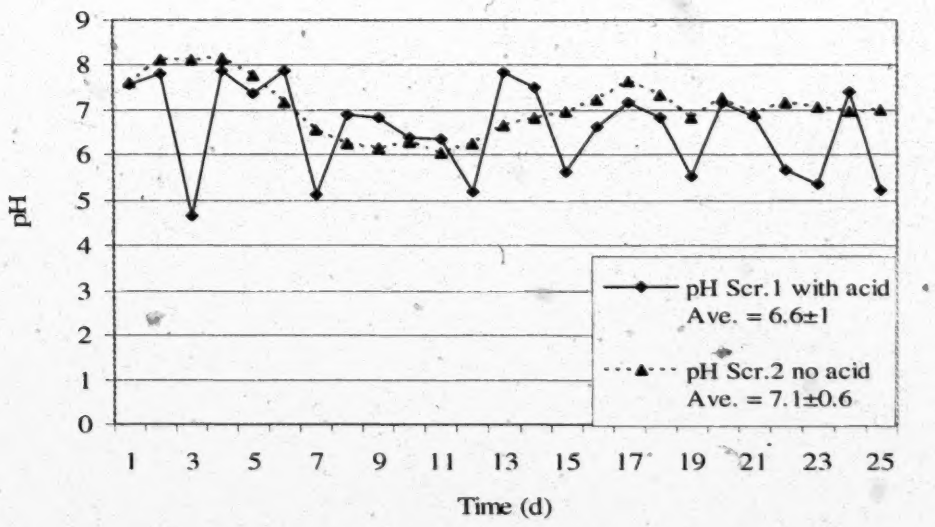


Figure 5.7 Comparison of pH values of the liquid of the bioscrubbers

The average pH values of the leachate from biofilters 1 and 2 were 7.9±0.2 and 7.7±0.2, respectively (Figure 5.8). The variation of the pH values is low compared with those in the preliminary experiments that ranged between 3 and 8.5. However, the by-products concentration that we will discuss later helps to clarify the reason for stabilizing the pH values of the biofilters.

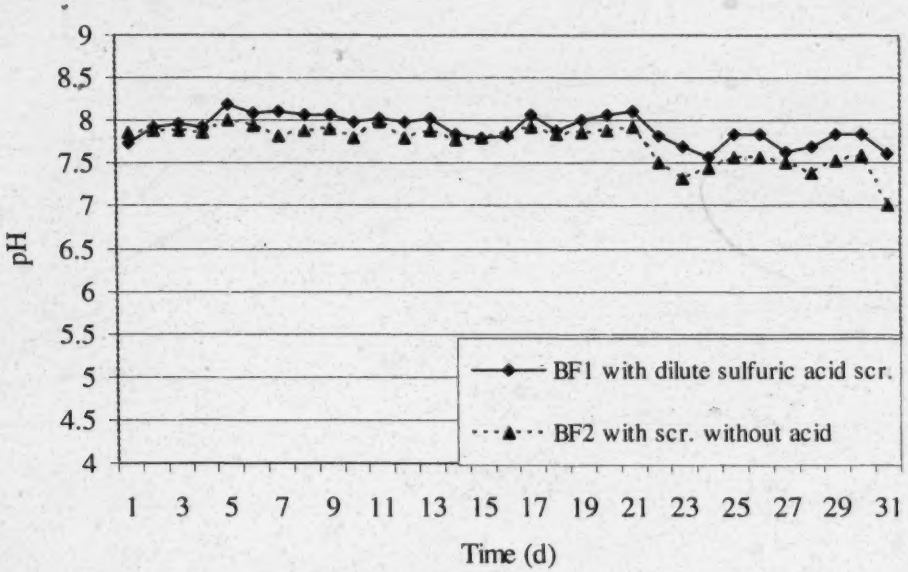


Figure 5.8 pH values of the leachates of the biofilters BF1 (dilute sulfuric acid) and BF2 operate with the bioscrubber 2 without acid

5.7.2 Concentrations of NH_3 and H_2S

Figure 5.9 shows the concentrations of NH_3 at the source (treatment plant), outlet of the bioscrubber 1, and outlet of the scrubber 2. On day 16 of the operation, the removal efficiency of the acid bioscrubber decreased because the acid solution was finished. However, it was understood that the removal efficiency of the bioscrubber with acid highly depends on the acid concentrations in the liquid of the biocrubber. The overall averages of the ammonia concentrations at the above locations were 21±5.2, 4±4.2, and 8±4.5 ppmv, respectively.

The overall averages of the H_2S concentrations at the above three locations were measured 3.0±1.6, 0.9±0.6, and 1.4±0.8 ppmv, respectively (Figure 5.10).

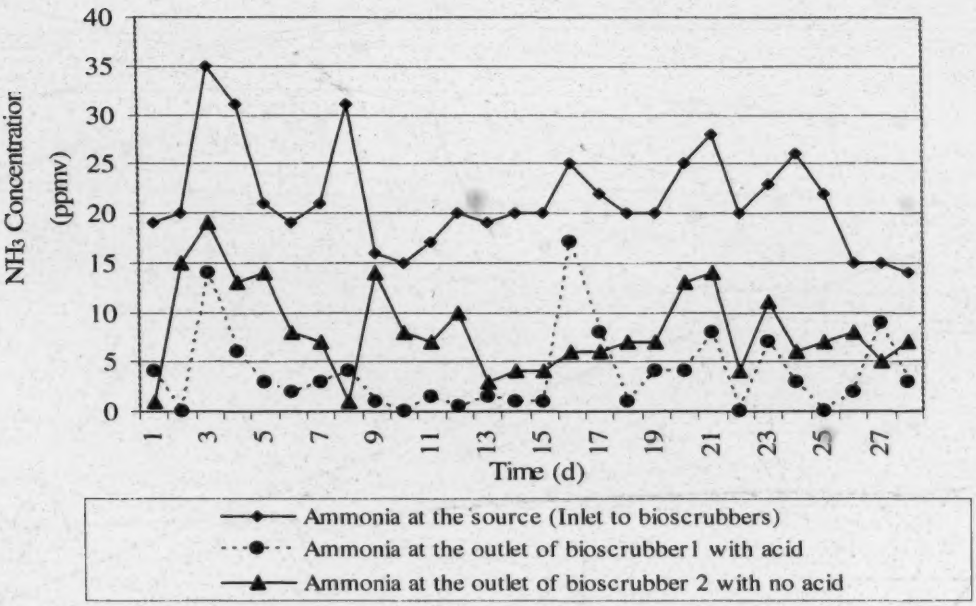


Figure 5.9 Inlet and outlet bioscrubber ammonia concentrations

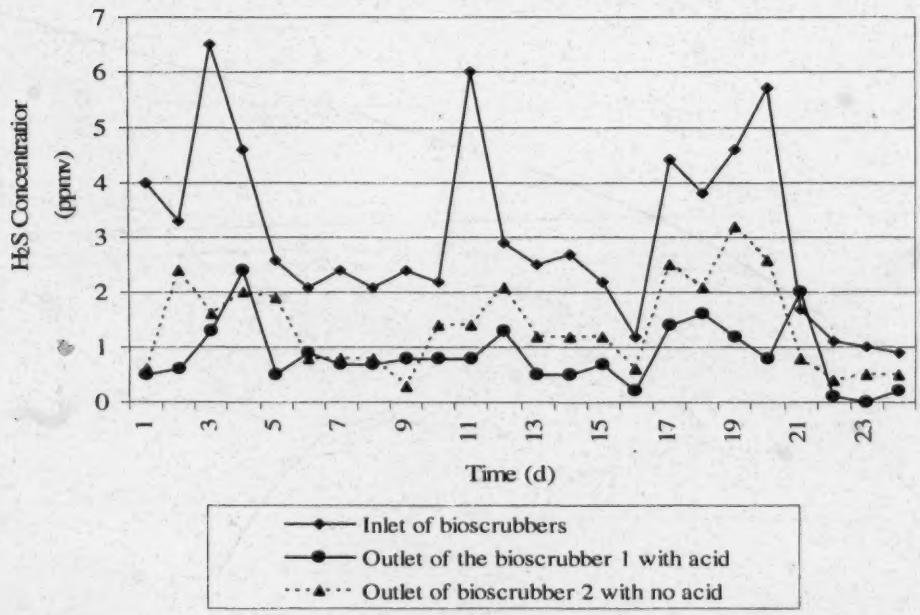


Figure 5.10 Hydrogen sulfide concentration at the inlet (treatment plant) and outlet of the bioscrubbers

5.7.3 Elimination Capacity (EC) and Removal Efficiency (RE)

As mentioned earlier in Chapter 2, the RE of a biofilter just shows the efficiency of the biofilter at specific operating conditions. EC, however, is a normalized factor that allows comparison of different biofilters with different conditions of operation. The EC and RE together appear to provide a better comparison of two biofiltration systems. The EC of the bioscrubbers were significantly different ($p<0.05$). The overall averages of the EC of the bioscrubbers with acid and no acid were 265±70 and 194±71 $g/m^3/d$, respectively (Figure 5.11). Obviously many factors affect the EC such as NH_3 concentrations, airflow, EBRT, temperature, and pH.

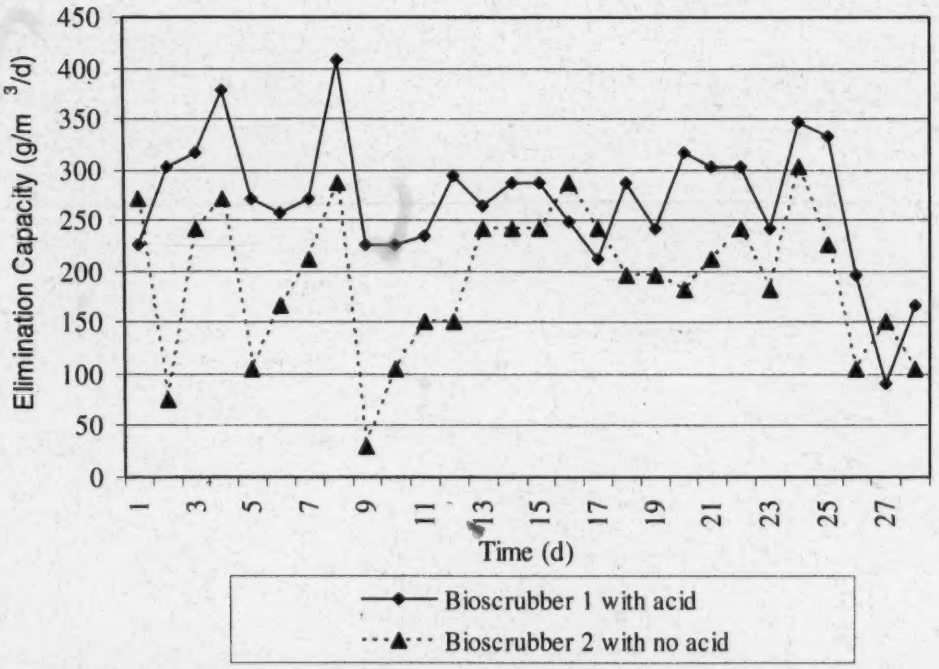


Figure 5.11 Elimination capacities of the bioscrubbers for ammonia operating in the treatment plant of the swine facilities at the University of Alberta

The removal efficiency (RE) of the bioscrubbers for ammonia was significantly different ($p<0.05$). The averages of the ammonia removal for the bioscrubber with acid and no acid were 83%±17.1 and 61%±19.7, respectively. The bioscrubber with acid absorbed the ammonia gas from the contaminated air and stabilized it to ammonium sulfate. The

bioscrubber 2 with no acid absorbed the ammonia from the polluted air (Figure 5.12) and eliminated it to nitrite that will be discussed later in the chemical tests. On day 16 of operation, the removal efficiency of the bioscrubber with acid decreased from 95% to 65% due to running out of acid.

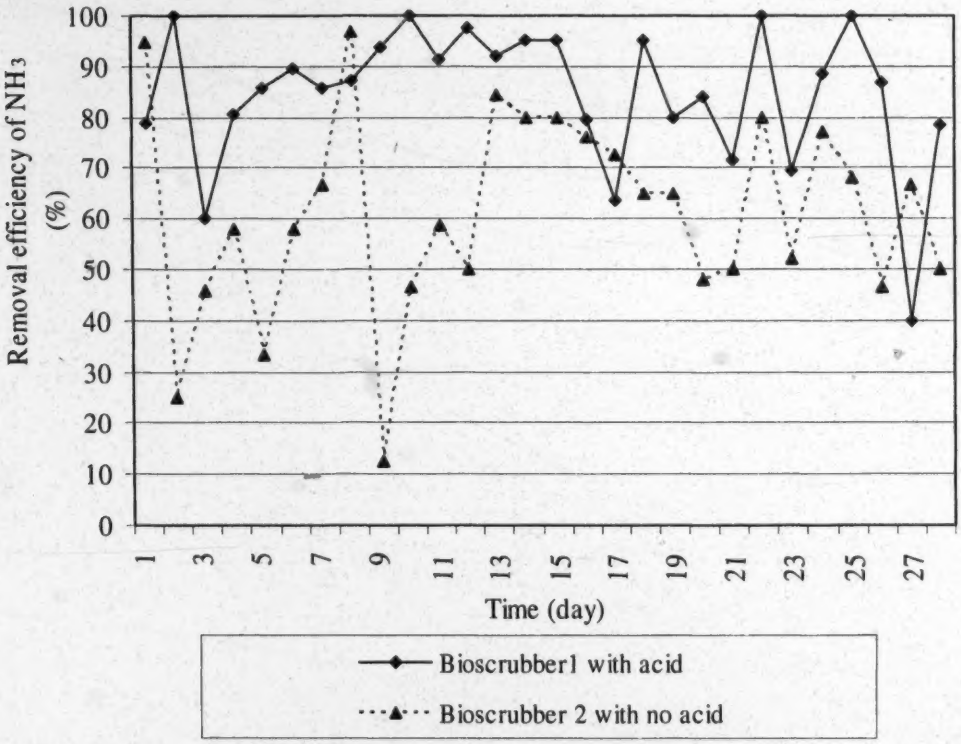


Figure 5.12 Removal efficiency of ammonia by bioscrubbers

Figure 5.13 shows the removal efficiency of the bioscrubbers for hydrogen sulfide.

The bioscrubber with acid removed hydrogen sulfide with a higher rate compared to the bioscrubber with no acid. Statistically, the RE of the bioscrubbers for hydrogen sulfide was significantly different ($P<0.05$). The averages of the hydrogen sulfide removal for the two bioscrubbers were 75.0±12.9 and 52.3±16 ppmv. The bioscrubber with acid reduced the hydrogen sulfide with the higher rate. This is probably due to the lower pH values because the microorganisms responsible for eliminating the hydrogen sulfide (*Thiobacillus* spp.) appear to tolerate the acidic environment.

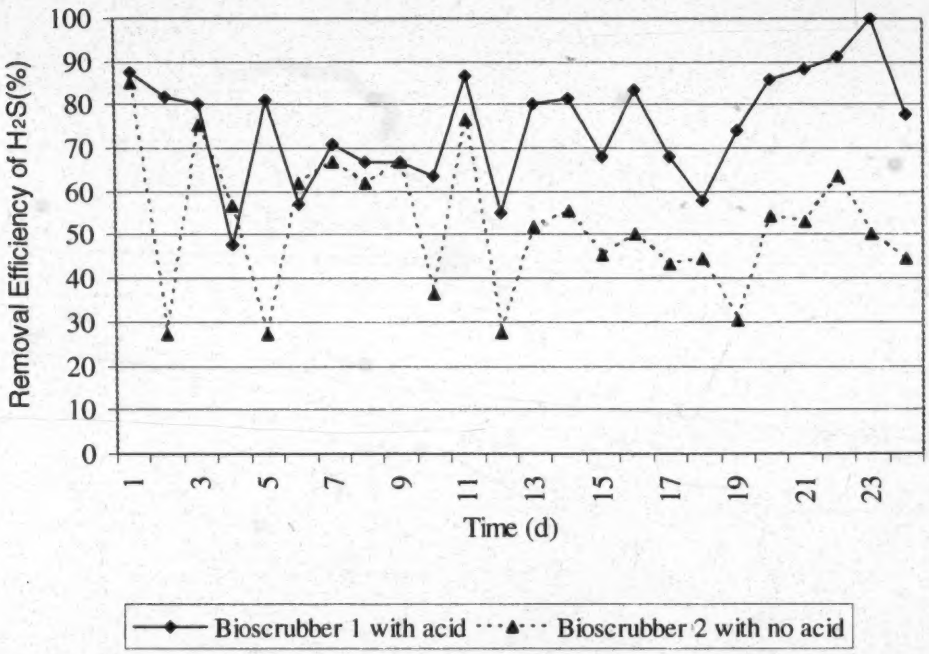


Figure 5.13 Removal efficiency of the scrubbers for hydrogen sulfide

5.7.4 Statistical Analysis

By using the statistical procedure (SAS, 2001), a t-test analysis was carried out for two treatments (using acid or no acid) on the important operational parameters such as temperature, pH, ammonia and hydrogen sulfide concentration at the inlet and outlets of bioscrubbers and biofilters, and removal efficiency and elimination capacity of the bioscrubbers. The summary results of the comparison of the bioscrubbers are shown in Table 5.2. The same statistical analysis was conducted for comparison of the operational parameters of the biofilters (BF1 operated with acid Scr 1 and BF2). Table 5.3 shows the results of the comparison of the biofilters. The pH values of the liquid of bioscrubbers were not significantly different ($P<0.05$) because the variation of the pH in the scrubber with acid was high. Bioscrubber 1 (sulfuric acid) had significantly higher elimination capacity (EC) and removal efficiency (RE) for ammonia and hydrogen sulfide ($P<0.05$). Production of nitrite in Bioscrubber 1 was negligible (Figure 5.14). On the other hand, sulfate concentration in this bioscrubber increased sharply in the range of 3,000 to 9,000

ppm (Figure 5.15). This means that chemical reactions between ammonia and sulfuric acid (equation 5-8) seem to be dominant for removal of ammonia. However, in Bioscrubber 2, nitrite was produced dominantly with the range of 1,500 to 4,800 ppm. Nitrate was produced with the range of 20 to 70 ppm. Moreover, sulfate was produced in this bioscrubber slowly, with a range of 800 to 1,500 ppm (Figure 5.15).

Table 5.2 Results of the statistical analysis comparing the two bioscrubbers (with sulfuric acid and no acid)

Variables	Scr. 1 (with acid) Ave.±SE	SD	Scr. 2 (no acid) Ave. ± SE	SD	P-values
Inlet temp. (°C)	27.7±0.3	1.6	26.5±0.3	1.4	0.0035
Outlet temp. (°C)	19.7±0.2	1.1	19.6±0.2	1.1	0.5811
pH	6.6±0.2	1.0	7.1±0.1	0.6	0.0585
NH_3 in (ppm)	21.4±1.0	5.2	21.4±1.0	5.2	-
NH_3 out (ppm)	3.9±0.8	4.2	8.2±0.8	4.5	0.0005
EC ($g/m^3/d$)	264.7±13.2	69.8	193.7±13.4	70.7	0.0004
RE NH_3 (%)	83.0±3.2	17.1	61.0±3.7	19.7	<0.0001
H_2S in (ppm)	3.0±0.3	1.6	3.0±0.3	1.6	-
H_2S out (ppm)	0.9±0.1	0.6	1.4±0.2	0.8	0.0150
RE H_2S (%)	75.0±2.6	12.9	52.3±3.2	16.0	<0.0001

The pH of the leachate of the biofilters was significantly different $P < 0.05$ (Table 5.3). The leachate of biofilter 2 had lower pH even though the rate of nitrification for both biofilters for nitrite and nitrate production was similar (Figures 5.16 and 5.17). The reason for low pH is the higher production of sulfate (Figure 5.18). Table 5.3 shows that EC and RE of the biofilters for NH_3 were significantly different ($P<0.05$). This is reasonable since biofilters 1 and 2 received significantly different ammonia concentrations. The average EC of biofilters 1 and 2 were 25.0±4.5 and 54.7±5.3 $g/m^3/d$, respectively and the concentrations of ammonia that these biofilters received were 3.9±0.6 and 8.2±0.8 ppmv, respectively.

Table 5.3 Results of the statistical analysis comparing biofilter 1 (scr.1 with dilute sulfuric acid) and biofilter2 (scr.2 with no acid)

Variables	BF1 (with acid Scr.) Ave.±SE	SD	BF 2 Ave.±SE	SD	P-values
Inlet temp. (°C)	19.7±0.2	1.1	19.6±0.2	1.1	0.5811
Outlet temp. (°C)	19.6±0.2	1.2	19.6±0.2	1.1	0.9003
pH of the leachate	7.92±0.03	0.16	7.76±0.03	0.19	0.0015
NH_3 in (ppm)	3.9±0.6	3.3	8.2±0.8	4.5	<0.0001
NH_3 out (ppm)	0.3±0.1	0.7	1.4±0.5	2.5	0.0195
EC ($g/m^3/d$)	25.0±4.5	23.7	54.7±5.3	27.8	0.0001
RE NH_3 (%)	97±2.1	10.9	86.5±3.44	18.2	<0.0163
H_2S in (ppm)	0.9±0.1	0.6	1.4±0.2	0.8	0.0150
H_2S out (ppm)	0.5±0.1	0.5	0.66±0.0	0.2	0.1139
RE H_2S (%)	42.3±7.6	37.1	39.2±5.0	24.5	<0.7388

5.7.5 Chemical Measurement (chloride, nitrite, nitrate, and sulfate)

5.7.5.1 Bioscrubber Liquid

Preliminary experiments in the treatment plant showed that pH of the leachate of the biofilter gradually decreased, and as a result, the removal efficiency of the biofilter also dropped. Obviously, when considering the cause of acidification of the biofilter leachate, it is necessary to focus on the main by-product. Moreover, measurement of nitrite and nitrate and ammonium concentrations helps us to better understand the accumulation of these intermediate products and the toxicity for the microorganisms in the biofilter environment. Nitric acid, sulfuric acid, and hydrochloric acid are the final products of biodegradation of ammonia, hydrogen sulfide, and chlorinated hydrocarbons, respectively. Therefore, chemical tests, including the measurements of nitrite, nitrate, sulfate, and chloride, were conducted weekly on the liquid of the bioscrubbers and leachate of the biofilters. Figure 5-14 shows the concentration of nitrite in the bioscrubbers' liquid. The nitrite produced in Bioscrubber 1 (with acid) was negligible.

This suggests that the chemical reaction between sulfuric acid and ammonia (equation 5-8) should be dominant for removing the dissolved ammonia. Moreover, the nitrifying bacteria that are responsible for the nitrification do not grow well in the acidic environment (average pH values 6.6 ± 0.2) (Metcalf and Eddy, 1993). The range of nitrite concentrations in Bioscrubber 2 was from about 1,500 to 5,000 ppm. This means that the ammonia concentration in the contaminated air is a dominant odourant.

The range of nitrate concentration in both bioscrubbers was about 20 to 220 ppm. The accumulation of the nitrite (toxicity of nitrite) probably prevented the production of the nitrate. However, more research is needed to evaluate why nitrification processes stopped or slowed down in the stage of oxidizing nitrite to nitrate. Figure 5.15 shows the sulfate concentrations in the bioscrubbers liquid. Obviously bioscrubber 1 (with acid) has a high range of sulfate about 3,500 to 9,000 ppm. In bioscrubber 2, sulfate was produced slowly, with a concentration range of about 800 to 1,500 ppm.

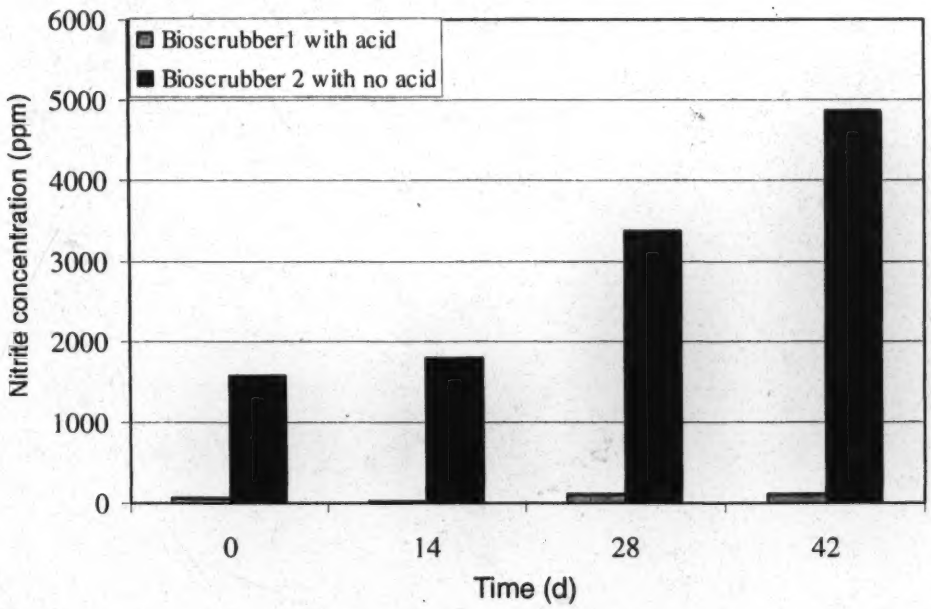


Figure 5.14 Nitrite in the liquids of bioscrubbers

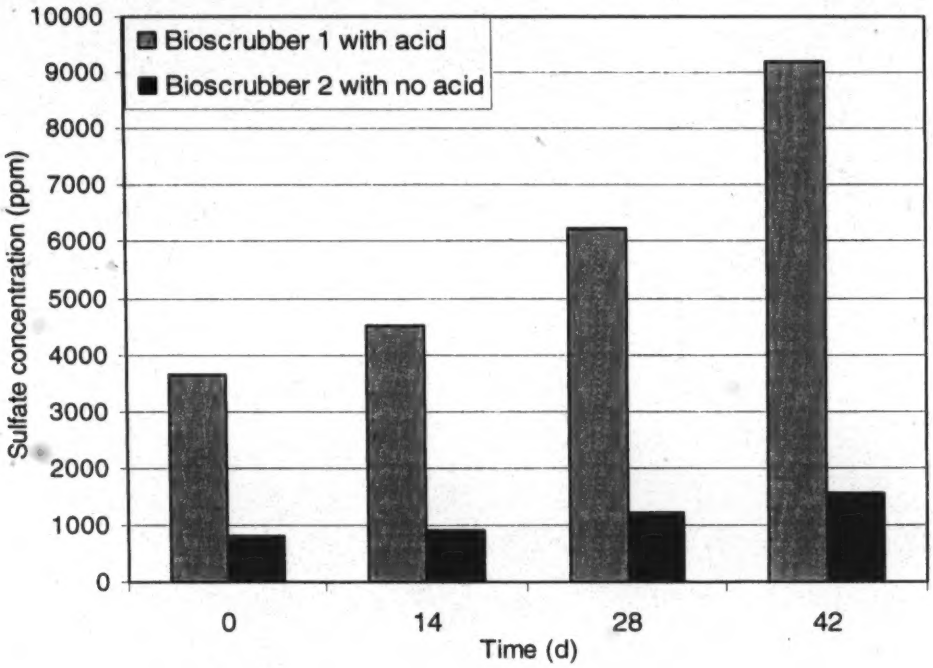


Figure 5.15 Concentration of sulfate in the liquid of the bioscrubbers

The concentration of chloride in the liquids of the bioscrubbers increased gradually from 10 to 20 ppm. This means that there were only low levels of chlorinated hydrocarbons in the contaminated air of the treatment plant (Figure 5.16).

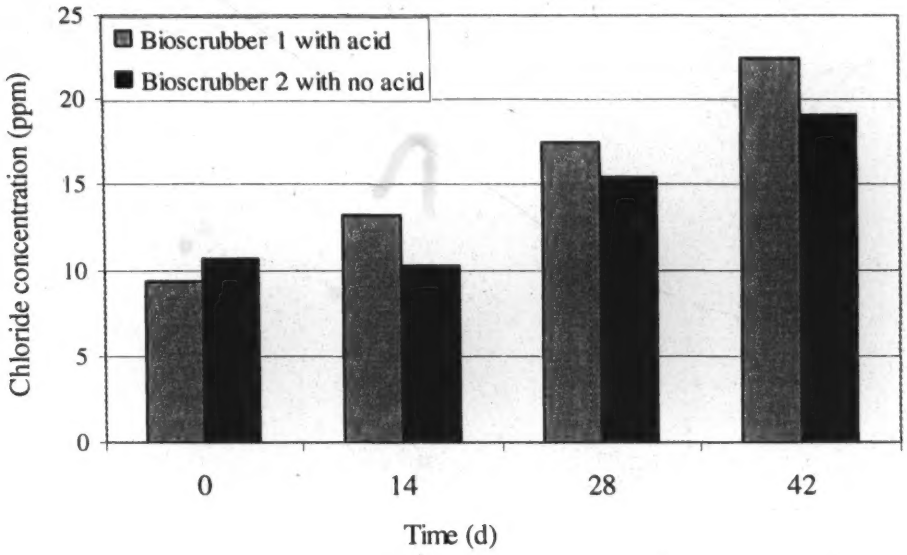


Figure 5.16 Chloride concentrations in the liquids of the bioscrubbers

5.7.5.2 Leachate of the Biofilters

Biofilter 1 received lower concentrations of ammonia and hydrogen sulfide, 3.9±4.2 and 0.9±0.6 ppmv, respectively, compared with 8.2±4.5 and 1.4±0.8 ppmv, for Biofilter 2. Figures 5.17 and 5.18 show that the products of nitrification process for degradation of ammonia to nitrite and nitrate were similar in the two biofilters. Probably the nitrification processes were limited by the microbial activity and not by ammonia loading. Although a portion of nitrite and nitrate production in the biofilters flushed out, there were still some accumulations of the nitrite and nitrate in the biofilters. These figures also show that the amounts of leachate from the biofilters are close to the optimum amount because the accumulation of these by-products was slow. On day 42, there was an increase in nitrite production in biofilter 2 and nitrate production in biofilter 1. Probably the variation of ammonia at the inlet of these biofilters caused this change.

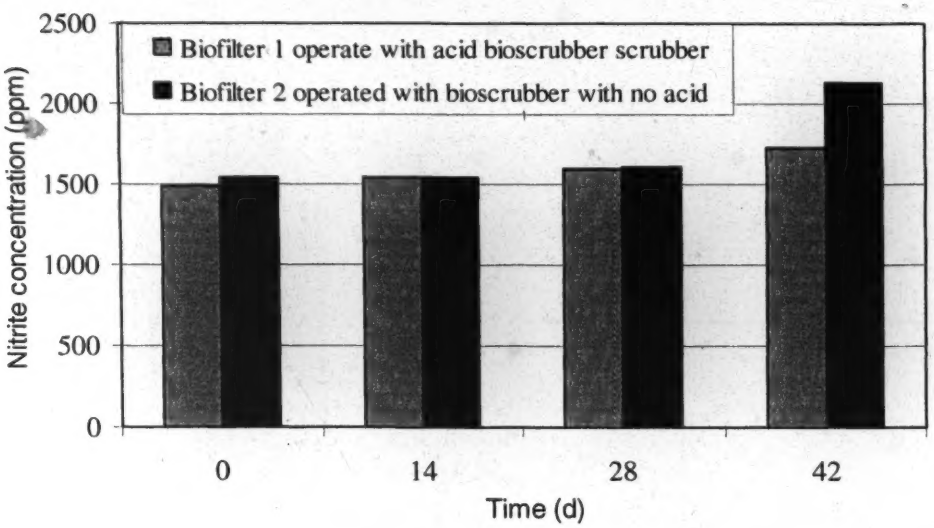


Figure 5.17 The nitrite concentration of the leachate of biofilters

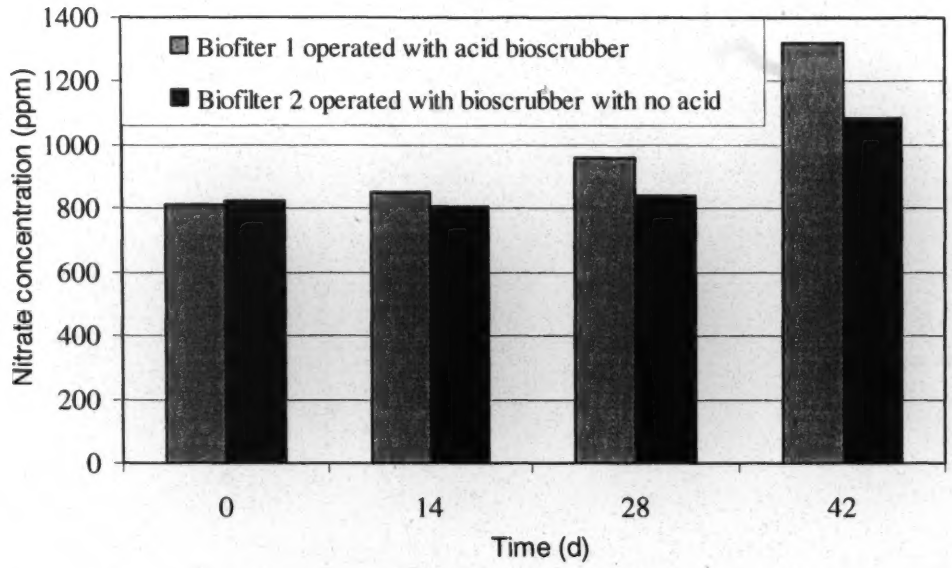


Figure 5.18 The nitrate concentrations of the leachate of the biofilters

The sulfate concentrations in the leachate of biofilter 1 increased from about 800 to 1,200 ppm. In the leachate of biofilter 2, the sulfate concentrations changed from 1,700 to 2,600 ppm. Higher sulfate accumulation occurred in biofilter 2 due to higher concentrations of H_2S (Figure 5.19). Higher production of sulfate caused a lower pH ($p<0.05$) in

comparison with the other biofilter. Now the question is why biofilter 1 which was operated with acid bioscrubber, had a higher pH value. Figures 5.17 and 5.18 show that the nitrite and nitrate production in both biofilter were similar but, at the same time, Figure 5.19 shows that the accumulation of sulfate in biofilter 2 was higher. This is confirmed by the higher concentration of H_2S (1.4±0.2 ppmv) that this biofilter received.

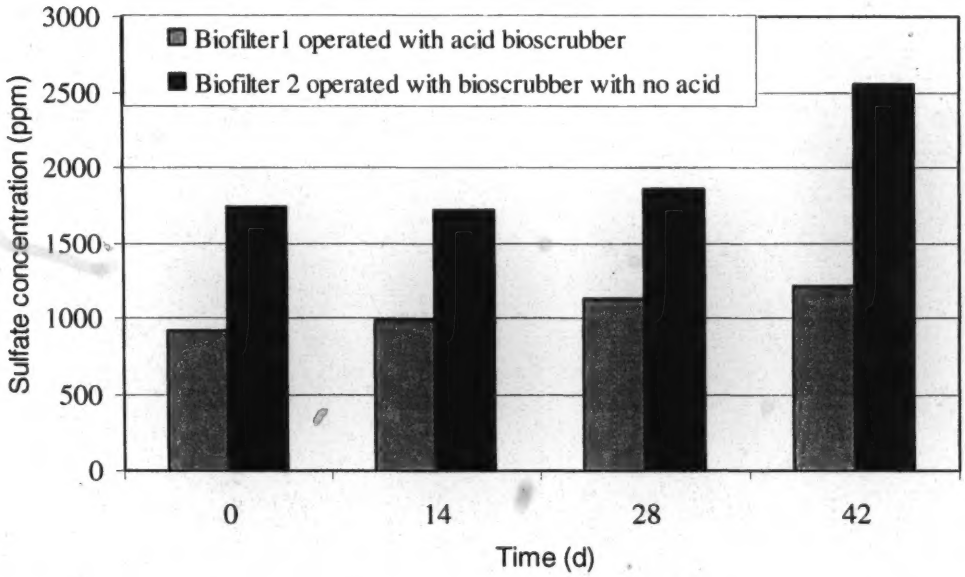


Figure 5.19 The concentration of sulfate in the leachate of the biofilters

5.7.6 Olfactometry

Table 5.4 shows the overall results of the measurement of the odour concentration based on the European standard (ASTM E-758, 1991). The odour concentration of the inlet contaminated air from the treatment plant during the experiment ranged from 466 to 1282 OU/m^3. The overall geometric mean of the inlet odour concentration was 676 OU/m^3. The overall odour concentrations at the outlets of bioscrubber 1, biofilter 1, bioscrubber 2, and biofilter 2 were 285, 230, 283, and 251 OU/m^3, respectively. These numbers show that the odour removal efficiencies of both biofiltration systems were similar. The bioscrubbers, with about 4s EBRT, reduced the odour concentrations by 58%. Bioscrubber 1, however, with dilute acid solution, had a significantly higher rate of NH_3

and H_2S reduction ($P<0.05$).

Each panelist, with a score between -5 and +5, assessed the hedonic tone of each sample. A score of -5 is most unpleasant, 0 is fresh air, and +5 is very pleasant. The hedonic tone of the exhaust air ranged between -1.7 to -3.4 with the overall average of -2.8. However, the data in Table 5.5 show that bioscrubbers and biofilters do not significantly change the hedonic tone of the exhaust air ($p=0.05$). Although previous work by Feddes et al. (2001a) indicated that hedonic tone can be a useful measure of odour character, more study is needed to investigate the effect on the hedonic tone of biofilter operation with higher than 10s EBRT.

Table 5.4 Odour concentrations at inlet and outlet of scrubbers and biofilters (OU_E/m^3)

Date (week)	Source	Scr1 outlet	Redn (%)	BF1 outlet	Redn (%)	Scr2 outlet	Redn (%)	BF2 outlet	Redn (%)
2	580	238		177		177		216	
2	580	215		195		238		216	
2 Ave.	**580**	**226**	**61**	**186**	**68**	**205**	**65**	**216**	**63**
4	535	308		354		406		268	
4	466	308		233		261		354	
4 Ave.	**500**	**308**	**38**	**287**	**43**	**326**	**35**	**308**	**38**
6	891	320		320		397		238	
6	1281	353		160		290		238	
6 Ave.	**1068**	**336**	**68**	**227**	**79**	**339**	**68**	**238**	**78**
Overall geomean	**676**	**285**	**58**	**230**	**66**	**283**	**58**	**251**	**63**

Scr1=Bioscrubber 1 (with sulphuric acid), Scr2= Bioscrubber 2, Redn=Reduction, BF1=biofilter 1, BF2=Biof.

Table 5.5 Hedonic tone results

Date (week)	Source	Scr1 outlet	Redn (%)	BF1 outlet	Redn (%)	Scr2 outlet	Redn (%)	BF2 outlet	Redn (%)
2	-3	-2.6		-2.7		-3.1		-1.9	
2	-1.7	-3		-3.3		-2.4		-2.3	
4	-3.4	-3.2		-2.8		-2.8		-3.6	
4	-3.4	-3.4		-3.6		-3.4		-3	
6	-2.9	-2.7		-2.6		-3.2		-3	
6	-2.4	-2.7		-2.1		-3.3		-2.3	
Ave.	**-2.8**	**-2.9**	**-4**	**-2.9**	**-4**	**-3.0**	**-7**	**-2.7**	**+4**

5.8 Conclusions and Recommendations

1. The removal efficiency of the bioscrubbers was different ($P<0.05$). The bioscrubber with the dilute (0.02%) sulfuric acid solution removed NH_3 (83%±3.2) and H_2S (75%±2.6), and the bioscrubber without acid removed NH_3 (61%±3.7) and H_2S (52%±3.2) from incoming air.

2. The overall average pH values of the scrubber liquid with and without acid were 6.6±1 and 7.1±0.6, respectively. Statistically, the pH values were not significantly different due to the high variations, especially in the acid bioscrubber.

3. The bioscrubber with acid had a statistically significant ($P<0.05$) higher elimination capacity for ammonia compared to the other bioscrubber without acid (265±13.2 and 194±13.4 g/m3/d).

4. Bioscrubbers with 4s retention time not only reduced the odour concentration up to 58%, but they also maintained the relative humidity of the inlet biofilter air at 95%. Combination of bioscrubber with no acid and biofilter removed the odour concentration by 63%. Odour removed by a combination of acid bioscrubber and biofilter by 66%.

5. Nitrite production in the bioscrubber with acid was negligible whereas concentration of nitrite in the bioscrubber without acid ranged from 1,500 to 5,000 ppm.

6. High concentrations of sulphate (up to 9,000 ppm) occurred in the bioscrubber with acid.

7. Lower pH occurred in the biofilter 2 because this biofilter received higher concentrations of hydrogen sulfide (1.4±0.2 ppm).

8. The elimination capacity (EC) of the biofilters 1 and 2 for ammonia was different. The mean values were 25±4.5 and 54.7±5.4 $g/m^3/d$, respectively.

5.9 References

ASTM E-758, 1991. Guidelines for Selection and Training of Sensory Panel Members. Philadelphia, PA.

Atlas, R. M. and Bartha, R. 1993. Microbial Ecology: Fundamentals and Applications (3rd edition). The Benjamin/Cummings Publishing Company, INC. California, USA.

Devinny, J. S., Deshusses, M.A., and Webster, T. S. 1999. Biofilteration for air pollution control. Lewis, Florida, USA.

Feddes, J.J.R., G.Qu, C. A. Quellette and J. J. Leonard. 2001. Development of an eight-panelist single port, forced-choice, dynamic dilution olfactometer. Canadian Biosystems Engineering 43: 6.1-6.5.

Feddes, J.J.R., I. Edeogu, B. Bloemendaal, S. Lemay and R. Coleman. 2001a. Odour reduction in a swine barn by isolating the dunging area. In proceedings of the 6th International Symposium on Livestock Environment, eds. Richard R. Stowell, R. Bucklin, and R. w. Bottcher, 278-284. St. Joseph, MI: ASAE.

Haug, R. T., 1993. The Practical Handbook of Compost Engineering. Lewis, Florida, USA.

Hodge, D. S., V. F. Medina, Y. Want and J. S. Devinny. 1992. Biofiltration: application for VOC emission control. 47th Purdue Industrial Waste Conference Proceedings, p. 619-618.

Islander, R. L., Devinny, J. S., Mansfeld, F., Postyn, A., and Shih, H., 1991. Microbial ecology of crown corrosion in sewers, J. Environ. Eng., 117 (6), 751.

Leson, G. and Winer, A. M. 1991. Biofiltration: an innovative air pollution control technology for VOC emissions. Journal of Air Waste Management Association, 41(8), 1045-1054.

Metcalf & Eddy, 1993. Wastewater Engineering: Treatment, and reuse (4rd edition). McGraw-Hill, Inc. New York. NY.

Metcalf and Eddy, Inc. 1991. Wastewater engineering: Treatment, disposal, and reuse (3rd edition). McGraw-Hill, Inc. New York. NY.

SAS Institute Inc. 2001. Software Release 8.2 (TS2M0), Cary, NC. USA.

Yang,Y. and Allen, E. 1994. Biofiltration control of hydrogen sulphide. 1. Design and operation parameters. Journal of the air and waste management association, 44: 863-868.

Yavorsky, J. 1993. Biofiltration for control of gas streams containing low concentrations of volatile organic compounds. Air & Waste management Association Annual Meeting, Denver, Colorado, June 13-18.

6. EXPERIMENT 2: THE EFFECT OF AMMONIA ON BIOFILTER PERFORMANCE

6.1 Introduction

Ammonia (NH_3), which is a colourless gas lighter than air, has a strong penetrating odour and dissolves readily in water. Microorganisms under aerobic and anaerobic conditions can produce it. Numerous factors have been shown to modify acute ammonia toxicity to microorganisms and aquatic animals in fresh water. Some factors change the concentration of NH_3 in the water by affecting the aqueous ammonia equilibrium, while other factors affect the toxicity of NH_3 itself, either ameliorating or intensifying its effects. Factors that have been shown to affect ammonia toxicity include pH, temperature, dissolved oxygen concentration, previous adjustment of microorganisms to ammonia, sporadic exposures, carbon dioxide concentration, salinity, and the presence of other toxic substances (WHO, 1986). The most studied of these factors is pH. Toxicity of NH_3 has been shown to increase as pH decreases (WHO, 1986). Information on the effects of temperature on NH_3 toxicity is limited and inconsistent, but there are indications that NH_3 toxicity is greater at low (<10°C) temperatures (Emerson et al., 1975).

Although ammonia has a detection threshold of 17,000 ppb and a recognition threshold of 37,000 ppb, other odourants, such as hydrogen sulfide, have a detection threshold of 0.5 ppb and a recognition threshold 4.7 ppb (Schiffman and Bennet, 2001; ASCE, 1995). Quantitatively, more than 50% of the odourants in swine facilities include ammonia (Chen et al., 2004; Hartung, 1988). In preliminary experiments, average ammonia concentrations in the barn of about 10 ppmv were measured under normal operation, although levels up to 100 ppmv were measured in an enclosed dunging area (EDA) (Feddes et al., 2001a). There are three categories of degradability of odourous compounds: low, moderate, and good (Govind, 2001; Devinny et al., 1999). Ammonia is classified as a good degradable odourant. Therefore, if the technology of biofiltration is used for odour reduction in animal facilities, available ammonia should be degraded to nitrite and nitrate (equations 6-1, 6-2, and 6-3).

$$NH_3 + H_2O \longleftrightarrow NH_4^+ + OH^- \quad (6\text{-}1)$$

Nitrosomonas sp.

$$NH_4^+ + 1\frac{1}{2}O_2 \longrightarrow NO_2^- + 2H^+ + H_2O \quad (\Delta G = -66kcal) \quad (6\text{-}2)$$

Nitrobacter sp.

$$NO_2^- + \frac{1}{2}O_2 \longrightarrow NO_3^- \quad (\Delta G = -17kcal) \quad (6\text{-}3)$$

There is a lack of information about the effect of ammonia concentration on the biofiltration system and accumulation of by-products such as nitrite and nitrate in the biofilter media. On the basis of preliminary experiments, a biofiltration system was designed as a combination of four biofilters and a bioscrubber (Figure 6.1). For simulation of contaminated air with low and high levels of ammonia concentrations, pure ammonia was injected into three of the biofilters after the bioscrubber to maintain ammonia concentration of 20, 45, and 90 ppmv at the inlet of these biofilters. This biofiltration system was operated for 50 days with three replications in the swine barn at the swine facility of the University of Alberta. The experiment was conducted in the barn in the cold season based on two rationales: having relatively stable temperature in the biofilter and preventing heat lost. Temperature, pH of the leachate, daily quantity of the leachate, ammonia and hydrogen sulfide concentrations, relative humidity (RH), airflow, nitrite, nitrate, and sulfate concentrations in the leachate of the biofilters were measured. The data provided through the measurements of the different parameters not only support this chapter for evaluation of the effect of ammonia on the biofilter functionality but also support chapter 7 (water application in the biofilters) and chapter 8 (mass balance). It also provides a prediction model for designing and operating biofilters in animal facilities.

6.2 Objectives

1) To operate a combination of bioscrubber and biofilter in the swine barn and measure the operational factors (temperature, pH of the leachate, daily quantity of the leachate, ammonia and hydrogen sulfide concentrations, relative humidity (RH), airflow, nitrite, nitrate, and sulfate concentrations of leachate).

2) To evaluate bioscrubber and biofilter (EC, RE, odour reduction, and production of by-products).

6.3 Materials and methods

6.3.1 Bioscrubber and Biofilters

One bioscrubber and four biofilters were constructed to treat ambient air in a feeder barn located at the Edmonton Research Station, University of Alberta (Figure 6.1). The top of each biofilter is closed with a plywood lid, which could be removed for servicing. A fan (Model: Blowr AMV-245 W. A Quality Canadian Product Ltd, Edmonton, AB) was installed at the top of each biofilter to draw about 20 L/s of air from the bioscrubber. Each biofilter has a cylindrical shape and was made of plastic material, with a diameter of 0.56 m, a height of 1.20 m, and a total volume of 300 L.

The bioscrubber also has a cylindrical shape and is made of plastic material, with a diameter of 78 cm, a height of 1.27 m, and a total volume of 575 L. A plastic screen was installed at a height of 20 cm from the bottom. A 200 L container was used for water circulation in the bioscrubber. Expanded polystyrene (EPS) was used as the bioscrubber media (320 L). The particle density of this material was 16 g/L. The EPS has a high absorbability of water (Beaver Plastics Ltd., Edmonton, AB). The function of the bioscrubber is to absorb the dust, increase the humidity of the air, and reduce the ammonia and odourous material concentrations. To prevent compaction of the materials in the biofilters, each biofilter was designed with three layers (0.25 m height of material in each layer) and 0.10 m of empty space between the layers. Painted metal meshes with a size of 5mm were used to support each layer, and a 0.30 m height air inlet plenum was created at the bottom of each biofilter. Each layer consisted of 50 L of coarse compost to give a total of about 150 L of compost material for a biofilter. The material included some bark and wood particles. The porosity of the wet bulk material at the end of the trial 1 and 2 measured 43% based on the procedure that was explained in chapter 2. Figure 6.2 shows the size distribution of the compost materials that were used as biofilter media (KC Environmental Group Ltd, Edmonton, AB).

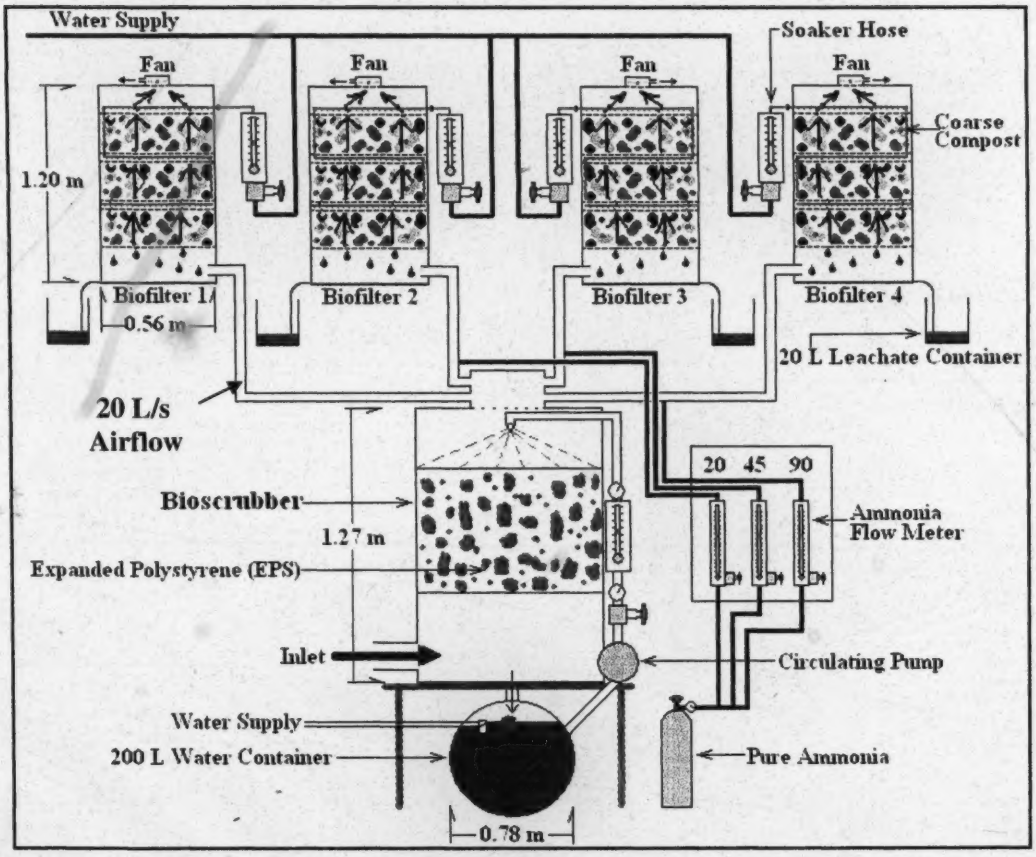


Figure 6.1 Schematic diagram of bioscrubber and biofilter

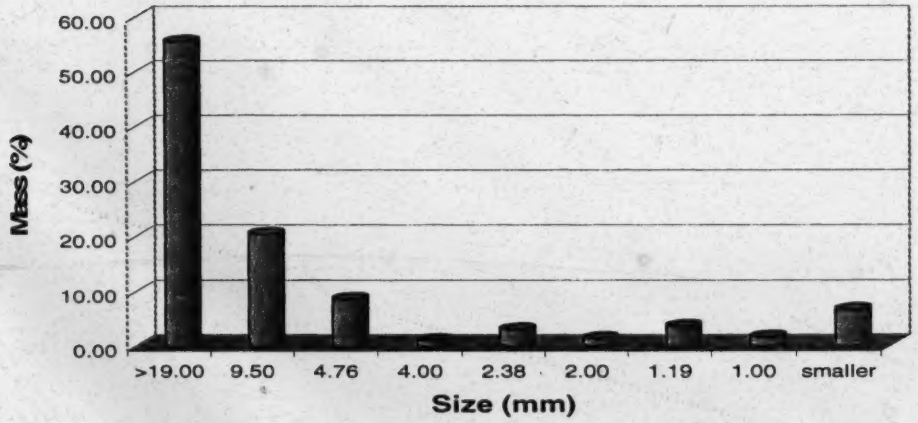


Figure 6.2 Particle sizes of compost materials used in the biofilters

6.3.2 Water Application

A circulating pump (Model 7PN, A.O. Smith Corp, Seattle, WA.) supplies water to the bioscrubber container. The average flow rate of the circulating water in the bioscrubber is 41 L/min. The total volume of the bioscrubber's circulating water is 200 L. In order to restore the amount of water the scrubber lost evaporation, a float valve was installed inside the bioscrubber container to maintain the amount of water at a set level. The amount of water used in the bioscrubber depends on temperature and RH of the barn air. Water is applied to each biofilter with an 8 m soaker hose, which spiraled through the three layers of each biofilter. A programmable timer (Model 1507, Noma Consumer Electrical, Canada) with a solenoid-activated valve applies water to the biofilters twice a day for one minute per application. The flow rate from the soaker hoses is approximately 2.6 L/d. The overall mean moisture content of the biofilter media, in three layers for each biofilter, was measured at the end of trials 1 and 2 (69±1%). The average pH of the tap water used was 7.6.

6.3.3 Measurement of NO_2^--N and NO_3^--N and Overall Mass Balance in the Biofilters

Nitrite and nitrate concentrations in the leachate from the biofilters were measured biweekly (four 200 ml samples from daily leachates transferred the same day of the sampling to the soil science laboratory of the University of Alberta for testing the nitrite and nitrate). All the samples were analyzed according to standard methods for the examination of water and wastewater (APHA, 1999). The daily increase in leachate nitrite and nitrate concentrations between sampling days was determined by subtracting the concentrations of the days before and after that particular test day and divided by the time interval (14 days).

6.3.4 Instrumentation and Measurements

Air velocity was measured with a hot wire anemometer (VelociCalc Model 8350, TSI Inc., St. Paul, MN) at the outlets of each biofilter. The velocity was measured at 7 vertical and 7 horizontal locations, and the average was used as the velocity at that day. Figure 6.3 shows that the measurement of the airflow by this instrument is very similar to using

a Pitot tube and micro manometer.

Based on biweekly measurements and necessary adjustments (using electronic speed control) the airflow through each biofilter was maintained at about 19±2 L/s. The pressure drop across the bioscrubber and biofilters was measured at five locations (outlet of bioscrubber, outlet of biofilters) throughout the experiment, five days per week using a manometer (Dwyer Mark II, Dwyer Instrument Inc., Michigan City, IN).

Temperature was measured five days per week. Eight alcohol-in-glass thermometers (Model 14-997 Fisher brand, Taiwan) were installed at eight locations (center of the barn two meters above the floor, air at inlet of bioscrubber, water in bioscrubber, air at outlet of bioscrubber, and air at outlet of biofilters).

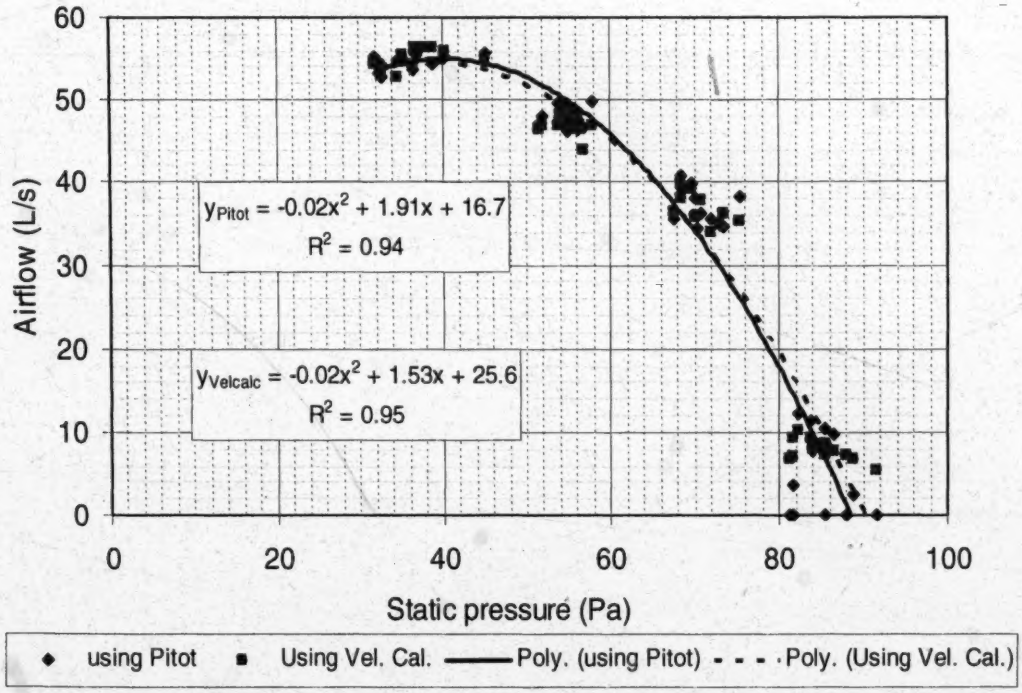


Figure 6.3 Airflow vs static pressure by using two methods of measurement (Velocicalc and pitot tube)

RH was measured five days per week using a psychrometer (Psychro-Dial Model CP-147, Environmental Tectonics Corp., Southampton, PA), at six locations (air inlet and outlet of bioscrubber and air outlet of biofilters).

Ammonia and hydrogen sulfide concentrations were measured at six locations (air inlet

and outlet of bioscrubber and air outlet of biofilters), five days a week. A sampling pump (Kitagawa Model 8014-400A, Matheson Tri-Gas, Pasippany, NJ) and appropriate detector tubes were used with accuracy ±10% for measuring ammonia concentrations. Hydrogen sulfide was measured by, Toxi Ultra instrument; S/n G24155 (accuracy ±10%), Biosystems, Inc. Middletown, CT. A small air pump (Gilian BDX II Abatement air sampler, Sensidyne Co., USA) provides 1L/min, contaminated airflow for the Toxi Ultra when it was operating. The pH of the bioscrubber liquid and biofilter leachate was measured for five days per week throughout the experiment using a pH meter, (Digi - Sence Model 5985 - 80, Cole Parmer Instrument Co., Chicago, IL). The electrical conductivities of four biofilter leachates were measured five days a week by using a digital conductivity meter (CO 150 Conductivity Meter Model 5015 Hach Company, Loveland, CO).

By measuring nitrite and nitrate concentrations, elimination capacity of the biofilters, and the amount of leachate collected, it was possible to evaluate the nitrification process in the biofilters using the assumption that leachate concentrations were representative of the concentrations in the liquid of the biofilter media. The nitrite and nitrate production data from the four treatments and three replications were considered as a complete block design with repeated measurements and were analyzed (SAS, 2001).

6.3.5 Experimental Design

This experiment was carried out with three replications (three trials) and four treatments (0, 20, 45, 90 ppmv NH_3 in the inlet air). Each replication lasted 50 days (14 days for adjusting the water flow and achieving biologically active biofilters, and 36 days for ammonia injection). Pure ammonia was used to provide the four levels of NH_3 concentration in the biofilter inlet air. To evaluate the effect of ammonia on the biofilters' performance, factors such as temperature, pH, RH, empty bed residence time (EBRT), removal efficiency (RE), and elimination capacity (EC) were measured. By calculating the EC as a normalized factor (airflow, volume of media, and time), there is a possibility of extending the results to biofilters with different sizes. To evaluate water application rates, factors that affect water application, such as temperature, relative humidity, and the amount of leachate from each biofilter, were measured daily and electrical conductivities

of the leachates were measured weekly. Also, chemical tests were conducted to evaluate the nitrification processes in the biofilters. The concentrations of nitrite, nitrate, and sulfate of the leachate from the biofilters were measured by the Soil Science laboratory at the University of Alberta. At the end of the third replication, operation of the biofilters was continued for an additional 28 days to evaluate water application rates to the biofilters. This will be discussed in Chapter 7. Additional water was applied to the biofilters using a timer that was set to apply water for an additional 30 s/d for the first 14 d. During the next 14 d, the timer was set to provide an additional minute daily. The amount of leachate water, temperature, RH, and electrical conductivity of the leachates was measured daily.

Air samples were collected in Tedlar sampling bags (Cat. No. 232-08, SKC Gulf Coast Inc Houston, TX) at the end of weeks 2, 4, and 6. Air was sampled at six locations (scrubber inlet, scrubber outlet, outlet of biofilters). Each sample comprised two sub-samples (i. e., two sample bags) giving a total of 12 sub-samples. The sub-samples were analyzed for odour concentration and hedonic tone using an eight-port, forced-choice olfactometer at the University of Alberta (Feddes et al., 2001).

6.4 Results

6.4.1 Barn Ambient Air Quality (NH_3, H_2S, and CO_2)

The mean values (averages ± SD) of ammonia concentrations of the barn ambient were 6.1±1.9, 8.4±2.0, and 11.5±4.5 ppmv for the trials 1, 2, and 3, respectively.

Differences between the ammonia concentrations throughout the trials may be due to lower ventilation rate resulting from colder weather (trial 1 took place from August 28 to October 19, trial 2 from November 12 to December 17, and finally, trial 3 from January 9 to February 15).

The concentrations of the ambient hydrogen sulfide of the barn during the three trials were 0.3±0.1, 0.3±0.2, and 0.3±0.2 ppmv for the trials 1, 2, and 3, respectively. The concentrations of hydrogen sulfide were similar and not affected by ventilation rate.

The ambient CO_2 concentrations of the barn were 959±125, 1451±265, and 1784±465 ppm for the trials 1, 2, and 3, respectively. The increase in trials 2 and 3 was due to decreased ventilation.

6.4.2 Temperature

Figure 6.4 shows the overall temperature means of air passing through the scrubber and biofilters. The results indicate that the temperature of the barn (location at the centre of the barn 2m from the floor) was different with the temperature of the air at the inlet of the bioscrubber (location 1m from the floor). The most noticeable air temperature drops in the combination of bioscrubber and biofilter occured when air passed through the bioscrubber as a result of evaporation. Temperature changes brought about by the biofilters afterwards were negligible.

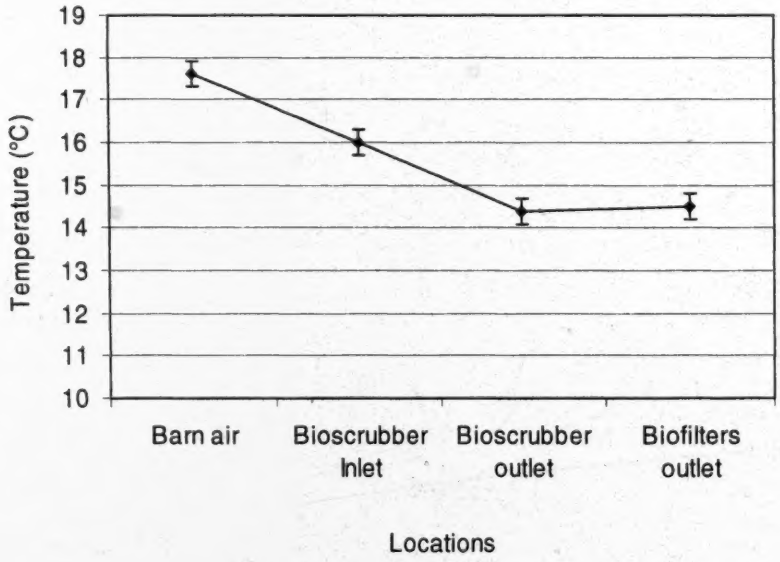


Figure 6.4 Overall average temperature means of contaminated air through the bioscrubber and biofilters

6.4.3 Relative Humidity (RH)

The overall average relative humidity (RH) of the air at the outlet of bioscrubber was 100%. However, the overall average relative humidity of the exhaust air from the biofilters was 91.5±2.4% (Table 6.1). There was no difference between the relative humidity of the air at the outlets of the biofilters ($P>0.05$) in each trial. The reason for the decrease of relative humidity from 100% to about 92% is not clear. Devinny et al. (1999) suggests there are two reasons why relative humidity in the porous media does not rise to exactly 100%. First, the initial layer of water molecules does not entirely shield the

second layer of water molecules from the effects of the support material. Secondly, a polar mineral will tend to polarize the water molecules adsorbing to it.

Table 6.1 Overall mean relative humidity (RH)

Trials	RH of bioscrubber (%)		Relative humidity at the outlets of biofilters (%)			
	Inlet Ave.±SD	Outlet Ave.±SD	BF1 Ave.±SD	BF2 Ave.±SD	BF3 Ave.±SD	BF4 Ave.±SD
1	53.9±8.9	100	93.8±2.5	93.6±2.4	93.1±2.3	93.5±2.4
2	46.8±3.9	100	91.2±2.0	91.4±2.2	91.3±2.0	91.7±2.3
3	45.3±7.0	100	90.5±3.0	90.0±2.4	89.2±2	89.1±3.4
Overall Ave.	49±6.7	100	91.8±2.5	91.7±2.3	91.2±2.1	91.4±2.7

6.4.4 Pressure Drop

The pressure drop in the bioscrubber increased from 25 to 75 Pa throughout 36 days of operation. In biofilters 1, 2, and 3, the pressure drop increased gradually from 70 to 80 Pa (Figure 6.5). The pressure drop in biofilter 4 operated with 90 ppmv of ammonia concentration on day 7 to 15 increased from 65 Pa to 110 Pa and then decreased to about 85 Pa. Reasons of unusual variation of pressure drop in this biofilter were not clear. However, the highest leachate was measured in this biofilter.

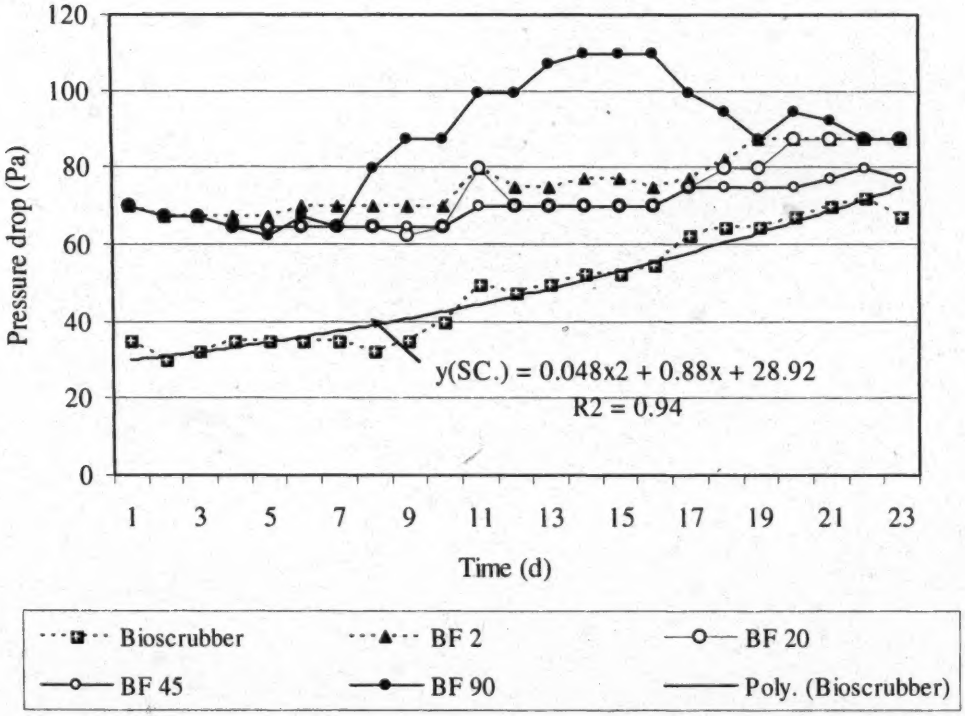


Figure 6.5 The pressure drop through the bioscrubber and biofilters in trial 1

6.4.5 pH

Ammonia nitrogen exists in aqueous solution as either the ammonium ion (NH_4^+) or free ammonia (NH_3). It is the free ammonia that is released from manure surfaces. Depending on the pH of the solution, NH_4^+ and NH_3 are coupled in equilibrium and in accordance with the equilibrium reaction 6-4.

$$NH_3 + H_2O \longleftrightarrow NH_4^+ + OH^- \qquad (6\text{-}4)$$

At pH levels above 7, the equilibrium is displaced to the left; at levels below pH 7, the ammonium ion becomes predominant. In other words, with the injection of ammonia gas to the aqueous solution, the pH value will be increased. Likewise, decreasing the ammonia injection decreases the pH value. The toxicity of the ammonium ion is much higher than the toxicity of the ammonia gas (Zhang et al., 1994; Metcalf and Eddy, 1993). Ammonia has a basic reaction when dissolved in the water because it reduces the hydrogen ion and produces ammonium. Based on Henry's Law and equation 6.4, different concentrations of ammonia injections are expected to produce various pH levels.

On the other hand, if ammonia is eliminated to nitrate, it can decrease the pH of the liquid (indirectly). However, Figure 6.6 shows the overall pH values of the biofilter leachates with ammonia injection concentrations from 0 to 90 ppmv.

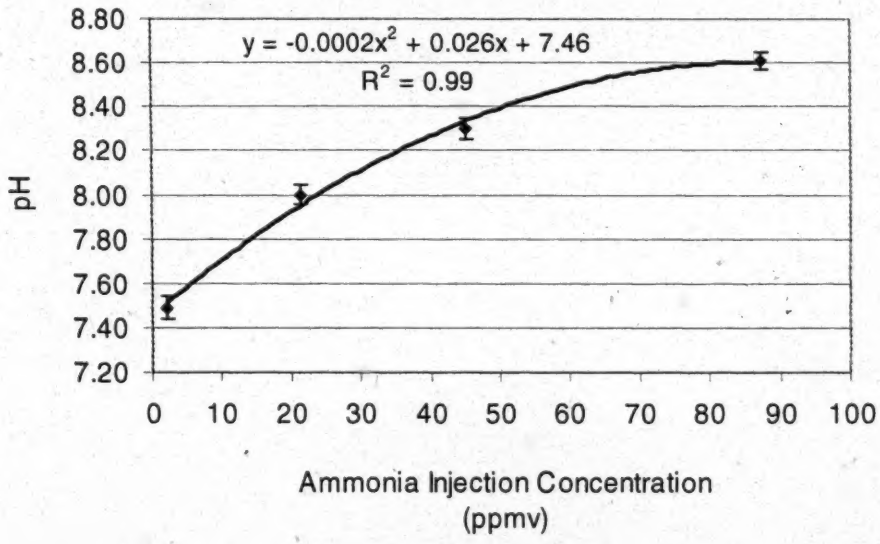


Figure 6.6 Mean pH values of the leachate of the biofilters for ammonia concentrations 2, 20, 45, and 90 ppm

6.4.6 Elimination Capacity (EC) and Removal Efficiency (RE)

Figure 6.7 shows the overall mean RE and EC values of the biofilters receiving between 0 to 90 ppmv ammonia concentrations. When the concentration of ammonia injection increased from 0 to 90 ppmv, RE decreased from 100 to 43.5%±5.9 and EC increased from 0.57 to 12 g/m^3/h. Under low loading conditions (2 ppmv ammonia), RE expected to be 100% because the biofilter has ability to eliminate all the ammonia enters to it to nitrite and nitrate, as a result, the EC is equal to the load. The ammonia EC and RE of a biofilter can be limited by microbial activities at high ammonia gas concentration (Henry's law).

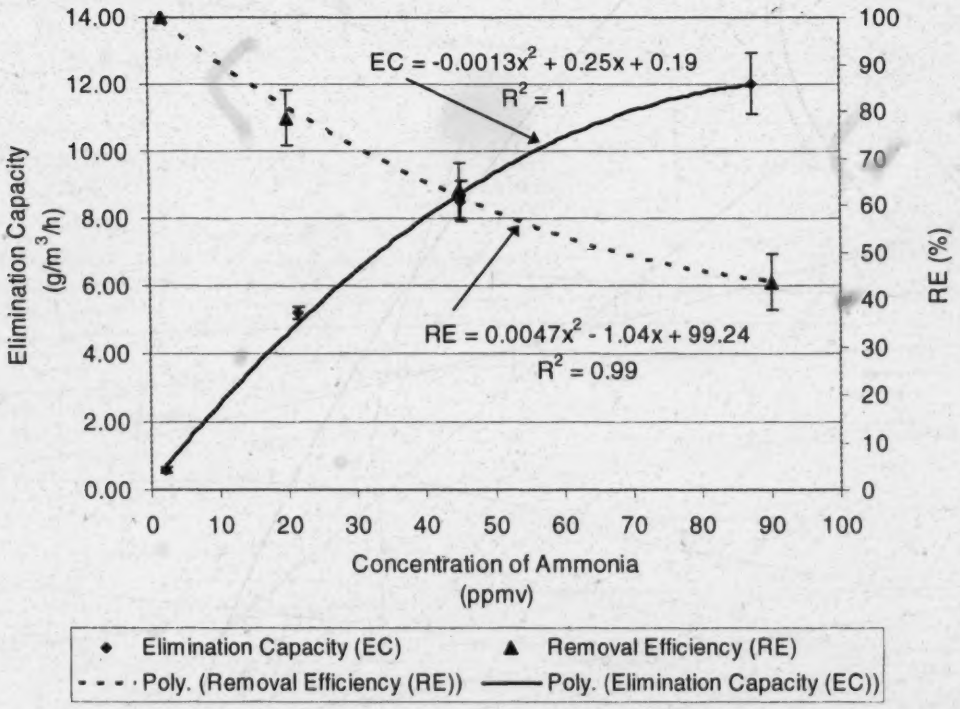


Figure 6.7 Elimination capacity and removal efficiency of ammonia vs concentration of ammonia

6.4.7 By-products and Nitrification Process

Table 6.2 shows the overall results of the measurement of the by-products (nitrite, nitrate, and sulphate) in the leachate of the biofilters. The sulfate concentrations of the leachate of the biofilters did not increase significantly. The overall averages were 142±73, 164±96, 162±66, and 224±124 ppm for the biofilters operated with 2, 20, 45, and 90 ppm ammonia concentrations, respectively. This is reasonable because, as mentioned earlier, the concentrations of the hydrogen sulfide was low in the barn (0.3±0.2 ppmv).

Table 6.2 The overall concentrations of nitrite, nitrate, and sulfate of the leachate of the biofiolters

Biofilters	Nitrite Ave.±SD (ppm)	Nitrate Ave.±SD (ppm)	Sulfate Ave.±SD (ppm)
BF1 (2 ppm)			
2 weeks	117±25	242±44	118±38
4 weeks	216±29	506±62	159±102
6 weeks	296±55	1,5863±354	148±80
Overall Ave.	**210±36**	**778±154**	**142±73**
BF2(20 ppm)			
2 weeks	387±152	188±108	118±52
4 weeks	1,702±387	680±287	200±134
6 weeks	4,029±640	2,204±1,129	174±101
Overall Ave.	**2,039±393**	**1,024±508**	**164±96**
BF3 (45 ppm)			
2 weeks	343±108	142±93	172±61
4 weeks	1,709±378	197±40	189±85
6 weeks	3,631±355	439±80	126±53
Overall Ave.	**1,894±280**	**259±71**	**162±66**
BF4 (90 ppm)			
2 weeks	203±58	39±30	263±132
4 weeks	647±171	92±75	208±114
6 weeks	2,435±993	128±100	202±126
Overall Ave.	**1,095±407**	**86±68**	**224±124**

In aqueous solutions, ammonia is present in the forms of free ammonia (NH_3) and ammonium ions (NH_4^+). In the first step of the nitrification process, ammonium changes to nitrite. In the next step, nitrite changes to nitrate. By measuring nitrite and nitrate concentration, the elimination capacity of the biofilters, and the amount of leachate, the nitrification process in the biofilter could be evaluated, assuming that leachate concentration is representative of the concentration in the liquid of the biofilter media. Table 6.3 shows the comparisons of the nitrite and nitrate production in the biofilters with 0, 20, 45, 90 ppmv ammonia injections.

Table 6.3 The comparison of nitrite and nitrate productions in the biofilters

Compound	NH_3 Injection Concentration			
	0 ppmv	20 ppmv	45 ppmv	90 ppmv
Nitrite	1.9±4.3 (a)	30.4±4.3 (b)	37.9±4.3 (b)	31.7±4.3 (b)
Nitrate	6.6±1.8 (a)	11.7±1.8 (b)	2.9±1.8 (a)	0.4±0.2 (c)

Note: Different letters along rows indicate differences ($p<0.05$).

Figure 6.8 shows the amount of nitrite and nitrate nitrogen production in the biofilters. The overall average of nitrate production were 6.6±1.8, 11.7±1.8, 2.9±1.8, and 0.40±0.2 $g/m^3/d$ for the biofilters with 0, 20, 45, and 90 ppmv ammonia concentrations, respectively.

There was significant difference in nitrate production between the biofilter with no ammonia injection and the biofilter with 20 and 45 ppmv ammonia injections, but these were not significantly different to biofilters with 45 ppmv ammonia injections. The results show that there were differences between nitrite production in biofilter 1, with no ammonia injection, and other biofilters with 20, 45, and 90 ppmv ammonia injection ($p<0.05$). Also, there were no differences between biofilters with 20, 45, and 90 ppm for nitrite production ($p>0.05$). It appears that when the concentration exceeds 20 ppmv of ammonia, the nitrification process is limited by microbial activity, not by ammonia loading.

The biofilter with 20 ppm ammonia produced the most nitrates (11.7±1.8 $g/m^3/d$), and the

biofilter with 90 ppmv ammonia concentrations produced no nitrate. The increase in ammonia concentrations, ammonium, and nitrite in the biofilter with 90 ppmv ammonia injections seems affected to the microorganisms for nitrate production.

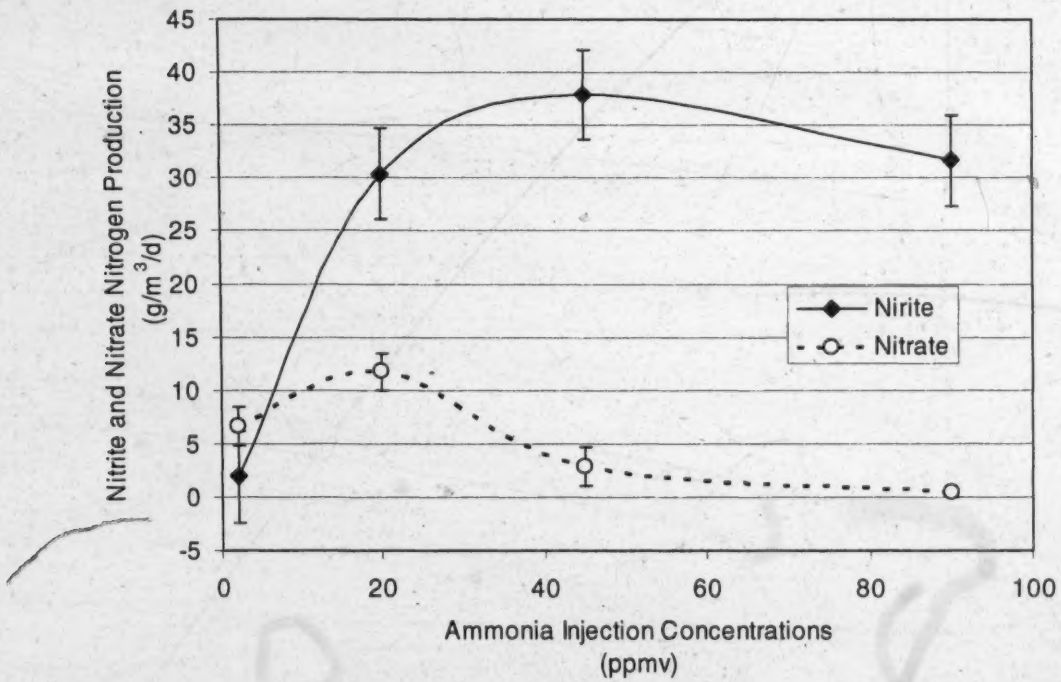


Figure 6.8 The mean nitrite and nitrate production in the biofilters that were operated at 2, 20, 45, and 90 ppmv ammonia

With a low level of ammonia in the air (2 to 10 ppmv), complete nitrification can take place in the biofilters (operated with 10s EBRT), producing nitrite and nitrate, because the critical EC (highest EC at RE = 100%) should be in this range of ammonia concentrations. However, the maximum elimination rate of the biofilters was 42.1±3.9 $g/m^3/d$. This amount is equal to the mass of ammonia that the biofilter can receive operating with 10s EBRT and 6 or 7 ppmv ammonia concentration, assuming RE = 100%. However, with complete nitrification it is expected the pH of the leachate will decrease slowly, when the H_2S concentration in the air is low (0.3 ± 0.2 ppmv). As a result, the sulfate ions should be negligible.

6.5 Correlation and Multiple Regression Analysis

Using the SAS (2001) procedure (Proc GLM, REG, STEPWISE), correlation and multiple regression analysis were carried out on the important factors such as pH, elimination capacity (EC), removal efficiency (RE), ammonia concentration at the inlet of biofilters (NH_3-In), total amount of NO_2^--N and NO_3^--N produced per day per m^3 of biofilter medium (TNpgd, $g/m^3/d$), and total amount of NO_2^--N and NO_3^--N washed out by the leachate (TNoutbw, $g/m^3/d$). The results for the biofilters with no ammonia injection, 20, 45, and 90 ppmv are shown in Tables 6.4, 6.5, 6.6, and 6.7, respectively.

Table 6.4 Correlation coefficients and p values with no ammonia injection. Number of observations=51

	pH	EC ($g/m^3/d$)	NH_3-In * (ppmv)	TNoutbw** ($g/m^3/d$)	TNpgd*** ($g/m^3/d$)
pH	1.00	0.36 0.0079	0.49 0.0002	0.09 0.5374	0.22 0.1250
EC ($g/m^3/d$)		1.00	**0.94** <0.0001	0.27 0.0596	0.31 0.0294
NH_3-In (ppmv)			1.00	0.24 0.0923	0.33 0.0205
TNoutbw ($g/m^3/d$				1.00	**0.90** <0.0001
TNpgd ($g/m^3/d$)					1.00

* NH_3-In = Ammonia concentration at the inlet of the biofilter (ppmv); ** TNoutbw = Total amount of NO_2^--N and NO_3^--N washed out by leachate water ($g/m^3/d$); *** TNpgd = Total amount of NO_2^--N and NO_3^--N produced ($g/m^3/d$).

In the biofilter with no ammonia injection, there was a highly positive correlation between EC and ammonia concentration (r= 0.94 and p<0.0001). This biofilter didn't receive additional ammonia. However, 100% of existing ammonia in the air stream was converted to nitrite and nitrate. Also, there was a high correlation (r=0.90 and P<0.0001) between total nitrite and nitrate production and total nitrite and nitrate that was washed

out with the leachate. However, there was a low positive correlation between EC and total nitrite and nitrate production (r=0.31 and P=0.0294). Also, there was a low positive correlation between EC and ammonia concentration that this biofilter received (r=0.33 and P=0.0205).

Table 6.5 Correlation coefficients and p values in biofilter 2 with 20 ppmv ammonia injection. Number of observations=51

	pH	EC ($g/m^3/d$)	RE (%)	NH_3-In* (ppmv)	TNoutbw* * ($g/m^3/d$
pH	1.00	-0.34 0.0153	**-0.53** <0.0001	-0.08 0.5833	**-0.71** <0.0001
EC ($g/m^3/d$)		1.00	**0.59** <0.0001	0.68 <0.0001	0.36 0.0108
RE (%)			1.00	-0.05235 0.7152	**0.63** <0.0001
NH_3-In (ppmv)				1.00	-0.07 0.6499
TNoutbw ($g/m^3/d$					1.00

* NH_3-In = Ammonia concentration at the inlet of the biofilter (ppmv); ** TNoutbw = Total amount of NO_2^--N and NO_3^--N washed out by water ($g/m^3/d$).

In biofilter 2, there was a negative correlation (r = -0.71 and P < 0.0001) between pH and total NO_2^--N and NO_3^--N washed out from the biofilter. At the same time, there was a positive correlation (r=0.43. P < 0.0019) between total NO_2^--N and NO_3^--N production and the amounts of NO_2^--N and NO_3^--N washed out from the biofilter. This means that by increasing the total amount of nitrite and nitrate, the pH will decrease. Also, there was a positive correlation between EC and ammonia concentration that this biofilter received (r = 0.68 and p <0.0001), and there was a positive correlation between total nitrogen washed out from the biofilter and removal efficiency of this biofilter (r = 0.63 and p < 0.0001).

Table 6.6 Correlation coefficients and p values in biofilter 3 with 45 ppmv ammonia injection. Number of observations=51

	pH	EC ($g/m^3/d$)	RE (%)	NH_3-In* (ppmv)	TNoutb** ($g/m^3/d$)	TNpgd** * ($g/m^3/d$)
pH	1.00	-0.28 0.00435	-0.20 0.1482	-0.09 0.5257	**-0.67** <0.0001	-0.32 0.0226
EC ($g/m^3/d$)		1.00	**0.72** <0.0001	**0.76** 0.0001	0.48 0.0004	0.47 0.0006
RE (%)			1.00	0.18 0.2031	0.51 0.0002	0.60 <0.0001
NH_3-In (ppmv)				1.00	0.16 0.2556	0.07 0.61
TNoutbw ($g/m^3/d$)					1.00	**0.78** <0.0001
TNpgd ($g/m^3/d$)						1.00

NH_3-In = Ammonia concentration at the inlet of the biofilter (ppmv); ,TNoutbw = Total amount of NO_2^--N and NO_3^--N washed out by water ($g/m^3/d$); TNpgd = Total amount of NO_2^--N and NO_3^--N produced ($g/m^3/d$).

In biofilter3, there was a positive correlation (r=0.78 and P<0.0001) between total N production and the washing of nitrite and nitrate. This means that by increasing the amount of water the total concentration of nitrite and nitrate washed out increases and, at the same time, production of these products increases. Also, in this biofilter there was a highly positive correlation between total ammonia concentration that this biofilter received and EC (r=0.76 and p < 0.0001). There was a negative correlation between pH of the leachate and total washed out nitrite and nitrate (r = -0.67 and P<0.0001). There was a negative correlation between pH and EC (r=-0.28 and P=0.0043). Also, there was a low negative correlation between pH and total nitrogen washed out (r=-0.33 and P=0.0226). There was a positive correlation between EC and total N washed out (r=0.49 and P=0.0004). Also, there were positive correlations between RE and total N washed out

or produced.

Table 6.7 Correlation coefficients and p values in biofilter 4 with 90 ppm ammonia injection. Number of observations=51

	pH	EC ($g/m^3/d$)	RE (%)	NH_3-In* (ppmv)	TNoutbw** ($g/m^3/d$)	TNpgd*** ($g/m^3/d$)
pH	1.00	-0.56 <0.0001	-0.60 <0.0001	-0.28 0.0416	**-0.77** <0.0001	**-0.74** <0.0001
EC ($g/m^3/d$)		1.00	**0.96** <0.0001	0.59 0.0001	0.20 0.1711	0.34981 0.0148
RE (%)			1.00	0.38 0.0058	0.24 0.0876	0.40 0.0047
NH_3-In (ppmv)				1.00	0.03 0.8119	0.09 0.5411
TNoutbw ($g/m^3/d$					1.00	**0.75** <0.0001
TNpgd ($g/m^3/d$)						1.00

NH_3-In = Ammonia concentration at the inlet of the biofilter (ppmv); TNoutbw = Total amount of NO_2^--N and NO_3^--N washed out by water ($g/m^3/d$); TNpgd = Total amount of NO_2^--N and NO_3^--N produced ($g/m^3/d$).

In biofilter 4, there was a positive correlation (r = 0.75 and p < 0.0001) between total production and washing out of total NO_2^--N and NO_3^--N. In this biofilter, there is a positive correlation (r=0.76 and p<0.0001) between ammonia concentrations at the inlet of the biofilter and EC.

Also in this biofilter, there was a strong positive correlation between RE and EC (r = 0.96 and p <0.0001). There was a high negative correlation between total washed out nitrite and nitrate and pH (r = -0.77 and p < 0.0001). This means that application of more water can decrease the pH value.

The result of multiple regression analyses of the data for biofilters with 20, 45, and 90 ppmv ammonia, are shown in Appendix E. For this analysis, it was assumed that RE was

the dependent variable and that the independent variables were: pH, EC, NH_3-in (ppmv), total nitrite and nitrate washed out by water (TNoutbw) ($g/m^3/d$), and total nitrite and nitrate produced per day (TNpgd) ($g/m^3/d$).

6.6 Odour Reduction

Figures 6.9, 6.10, 6.11, and 6.12 show the odour concentrations of the contaminated air at the inlet and outlet of the bioscrubber and biofilters. Tables 6.8 and 6.9 show a summary of olfactometry results during the entire experiment. There was high variation of the odour concentration at the source throughout the experiment. However, the bioscrubber reduced the odour concentration by 48%, 66%, and 73% in trials 1, 2, and 3, respectively. Biofilter 1, with no ammonia injection reduced the odour concentration by 25%. The overall odour reduction by the bioscrubber and biofilter with no ammonia injection was 72%. This rate of odour reduction with an overall 12 s EBRT is for combination of bioscrubber and biofilter. As Table 6.8 and above figures indicate, during trials 1 and 2, the geometric mean odour concentrations at the outlets of all biofilter with ammonia injections (20, 45, 90 ppm) were higher than those at the bioscrubber's outlet. However, because we did not measure the odour concentrations after the ammonia injections, we cannot indicate how much the odour concentrations increased by ammonia injections. Each panelist assessed the hedonic tone using scores between –5 and +5. A score of –5 is most unpleasant, 0 is odourless air, and +5 is very pleasant. The data in Table 6.9 shows that the bioscrubber improved the hedonic tone from -3.6 to -3.1 (11%) on average, and the biofilter with no ammonia injection improved the hedonic tone of the odour after the bioscrubber by 10%.

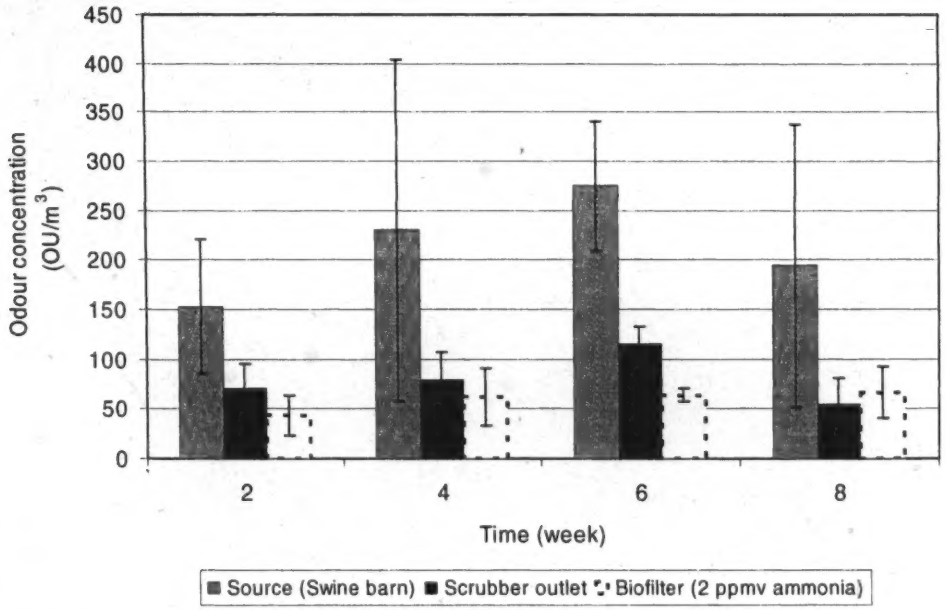


Figure 6.9 The odour reduction by the bioscrubber and biofilter operated in the pig facility with no ammonia injection to the biofilter

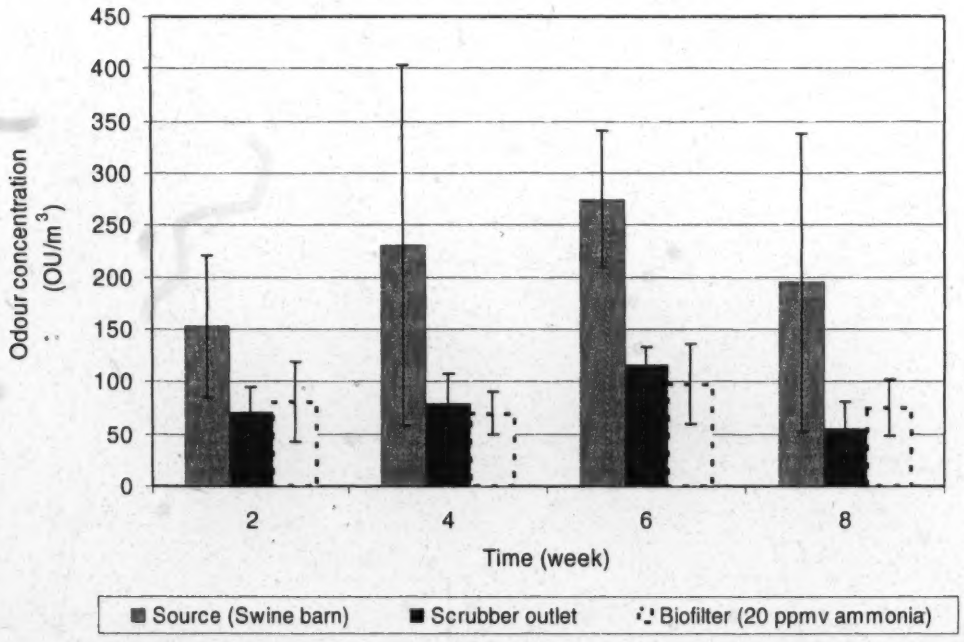


Figure 6.10 The odour reduction by the bioscrubber and biofilter operated in the pig facility with 20 ppmv ammonia concentrations to the biofilter

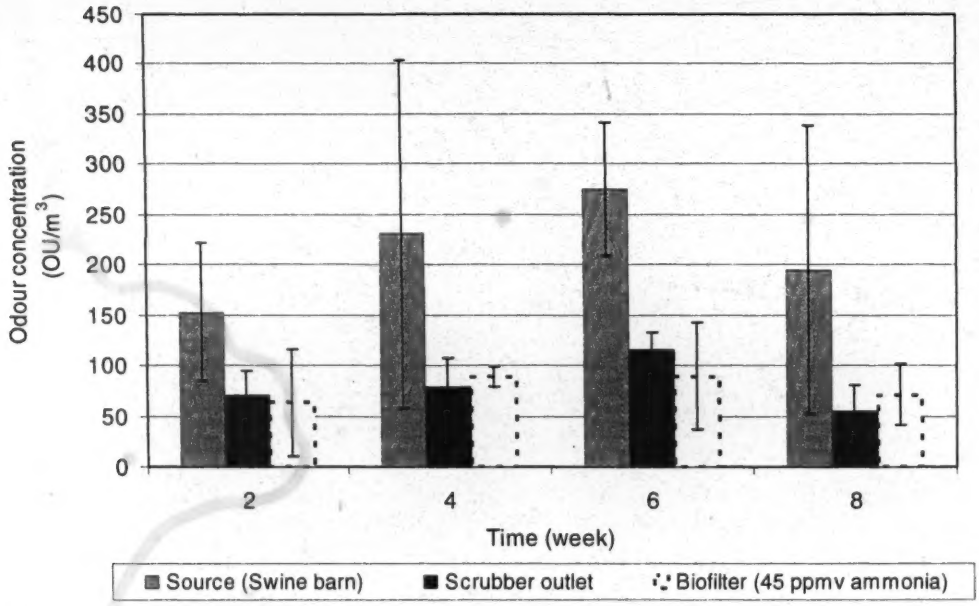


Figure 6.11 The odour reduction by the bioscrubber and biofilter operated in the pig facility with 45 ppmv ammonia concentrations in the biofilter

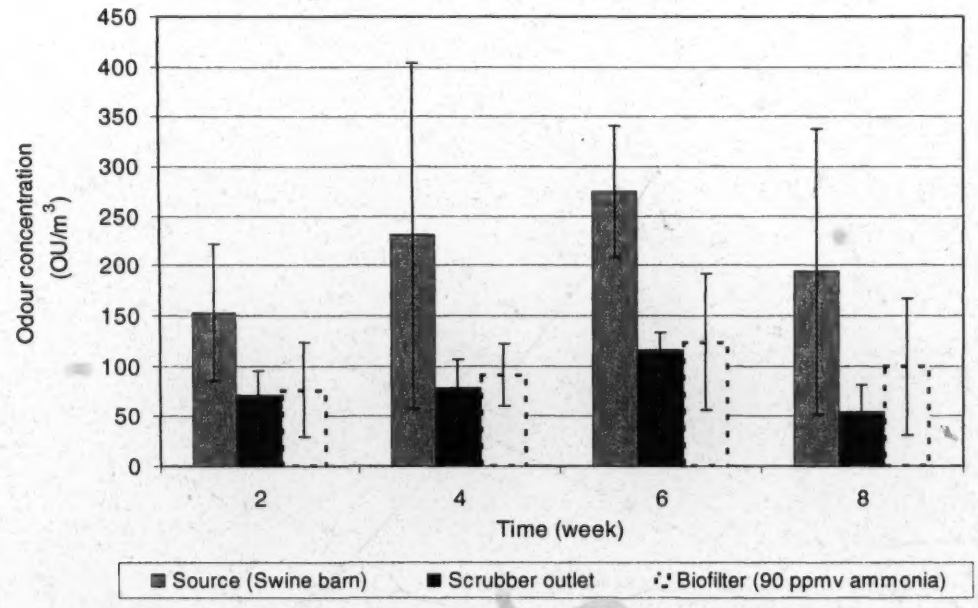


Figure 6.12 The odour reduction by the bioscrubber and biofilter operated in the pig facility with 90 ppmv ammonia concentrations in the biofilter

Table 6.8 Summary of olfactometry geometric means

Trial	Source (OU/m^3)	Scrubber outlet (OU/m^3)	Odour removal %	Biofilter (outlet)*			
				1 (OU/m^3)	2 (OU/m^3)	3 (OU/m^3)	4 (OU/m^3)
Trial 1	119±55	63±40	48	43±15	92±36	90±40	69±70
Trial 2	292±101	101±14	66	74±20	103±18	100±40	139±29
Trial 3	271±116	74±25	73	64±23	58±17	52±22	98±50
Overall	211±93	78±26	63	59±19	82±24	78±34	98±50

* Biofilters 1, 2, 3, and 4 operated with 0, 20, 45, and 90 ppmv ammonia injections, respectively.

Table 6.9 Average values of hedonic tones of the odour samples

Trial	Source	Scrubber outlet	Biofilter (outlet)*			
			1	2	3	4
Trial 1	-3.8±0.5	-3.3±	-2.9±0.7	-3.4±0.3	-3.1±0.2	-3.2±0.2
Trial 2	-3.4±0.6	-3.1±0.8	-3.1±0.7	-3.2±0.7	-3±0.6	-2.7±0.7
Trial 3	-3.2±0.6	-3.0±0.4	-2.5±0.5	-2.8±0.5	-3.0±0.2	-2.9±0.3
Overall	-3.5±0.6	-3.1±0.5	-2.8±0.6	-3.1±0.5	-3.0±0.3	-2.9±0.4

* Biofilters 1, 2, 3, and 4 operated with 0, 20, 45, and 90 ppmv ammonia injections, respectively.

6.7 Conclusions

1. The overall mean RH of the air at the scrubber inlet and outlet was 50 and 100%, respectively. Meanwhile, the overall average RH of the air at the outlet of biofilters was measured to be 92%. Statistically, there were no differences between the RH of the air at the outlets of the biofilters in each trial.

2. Ammonia concentrations of 2, 20, 45, and 90 ppmv significantly affected the elimination capacity (EC), removal efficiency (RE) of biofilters for ammonia, and pH of the biofilters.

3. The mean pH values were 7.49±0.04, 8.00±0.04, 8.3±0.04, and 8.6±0.04, for the

biofilters that received 2, 20, 45, and 90 ppmv ammonia concentrations, respectively.

4. When the concentration of ammonia increased from 0 to 90 ppm, RE of biofilters for ammonia decreased from 100 to 44± 5.9% and EC increased from 0.57 to 12 $g/m^3/h$ of ammonia nitrogen.

5. The biofilter with no ammonia injection reduced the odour concentrations up to 25% after the bioscrubber.

6. The pressure drop varied between 24.5 and 69 Pa through the bioscrubber and 59 to 88 Pa through the biofilters. EBRTs were estimated to be 4 and 8s for the bioscrubber and biofilters, respectively.

7. The results indicate that the large air temperature change occurred when air passed through the scrubber due to evaporation. The temperature changes through the biofilters were negligible. There were no significant differences ($P>0.05$) between the temperatures of the biofilters. The mean temperatures of the biofilters (BF1, BF2, BF3, and BF4) were 14.5±0.3, 15.0±0.3, 14.9±0.3, 14.7±0.3°C, respectively.

6.8 References

American Society of Civil Engineers (ASCE). 1995. Odour control in wastewater treatment plants. Library of Congress Cataloging-in-Publication Data: USA.

APHA. 1999. Standard methods for the examination of water and wastewater. American Public Health Association, Washington, D.C., p. [1 v. and 1 CD ROM].

Chen, Y., J. Yin, K. Wang, S. Fang, 2004. Effects of periods of nonuse and fluctuating ammonia concentration on biofilter performance. Journal of Environmental science and Health Part-A,-Toxic/Hazardous Substances and Environmental Engineering. 39(9): 2447-2463.

Devinny, J. S., M.A. Deshusses, and T.S. Webster, 1999. Biofilteration for air pollution control. Lewis Publishers, New York, USA.

Emerson, K., R.C. Russo, R.E. Lund, and R.V. Thurston, 1975 aqueous ammonia equilibrium calculations: effect of pH and temperature. J. Fish. Res. Board Can., 32: 2379-2383.

Feddes, J. J. R., G. Qu, C. A. Quellette and J. J. Leonard. 2001. Development of an eight-panelist single port, forced-choice, dynamic dilution olfactometer. Canadian Biosystems Engineering 43: 6.1-6.5.

Feddes, J.J.R., I. Edeogu, B. Bloemendaal, S. Lemay and R. Coleman. 2001a. Odour reduction in a swine barn by isolating the dunging area. In Proceedings of the 6th International Symposium on Livestock Environment, eds. Richard R. Stowell, R. Bucklin, and R.W. Bottcher, 278-284. st.Joseph, MI: ASAE.

Govind, R. 2001. (Unpublished paper) Biofiltration: An innovative technology for the future. University of Cincinnati, Department of Chemical Engineering, University Cincinnati, OH 45221-0171.

Hartung, J., 1988.Tentative calculations of gaseous emissions from pig houses by way of the exhaust air. In: Nielsen,V. C., Vooburg J., L' Hermite, P. (eds): Volatile emissions from livestock farming and sewage operations. London: Elsevier Applied Science, 54-58.

Metcalf and Eddy, Inc. (Revised by: G. Tchobanoglous, F.L. Burton, and H.D.Stensel) 1993. Wastewater Engineering: Treatment, and reuse (4rd edition). McGraw-Hill, Inc. New York. NY.

SAS Institute Inc. 2001. Software Release 8.2 (TS2M0), Cary, NC. USA.

Schiffman, S.S., and J.L. Bennett, 2001. Quantification of odors and odorants from swine operations in North Carolina. Agricultural and Forest Meteorology. 108: 213-240.

World Health Organization (WHO), 1986. Environmental Health Criteria 54. Ammonia. Accessed online at http://www.inchem.org/documents/ehc/ehc 54.htm on 2005/05/16.

Zhang, R. H., D. L. Day, L. L. Christianson, W. P. Jepson, 1994. A computer model for predicting ammonia release rates from swine manure pits. Silsoe Research Institute. UK.

7. THE EFFECT OF AMMONIA ON WATER APPLICATION

7.1 Introduction

Moisture content (M.C.) is essential for the survival and metabolic activity of microorganisms (Leson and Winer, 1991). The most dominant microorganism groups in biofilter media are bacteria, fungi, and actinomycetes. These microorganisms cannot be active in a dry environment although fungi have more tolerance than bacteria to environments with low moisture content. Air streams with less than 100% relative humidity (RH) can strip the moisture from the biofilter media, especially near the biofilter inlet where the highest volatile organic compound (VOCs) concentrations exist (Van Lith et al., 1997; Swanson and Loehr, 1997). In general, insufficient moisture content results in a low metabolic rate and growth of microorganisms resulting in incomplete biofiltration of treated gas. Excess moisture, on the other hand, can cause the formation of anaerobic regions, compaction, and clogging. Also, De Heyder et al. (1994) confirms that, for VOCs with low water solubility, excessive moisture content significantly decreased the mass transfer from the gas phase to the biofilm and resulted in a lower elimination rate. The optimum moisture content of biofilter materials ranges between 40 and 60 percent by wet weight (Ottengraf, 1986).

Williams and Miller (1992) recommend a degree of saturation greater than 95% in the waste gas inlet stream. Depending on the equilibrium M.C. of the medium, pre-humidification of the contaminated air is the preferred method to provide sufficient moisture and to prevent the drying of the biofilter media. Corsi and Seed (1995) and Leson and Winer (1991) suggest a saturation level of greater than 95% in the waste gas inlet stream. However, drying may still occur due to exothermic microbial activity unless the inlet humidity is increased to above 99% (Van Lith et al., 1997). Biofilters must operate in the range of water content between the field capacity, which is the amount of water remaining in a medium when the downward water flow, which is due to gravity, becomes negligible and the minimum necessary water content for high biological activity. In this range of water content, the RH of air in equilibrium with the media is only slightly below 100%. Small changes in RH ultimately can result in very large changes in medium water content. Consequently, RH should be measured and controlled

very accurately but, unfortunately, RH measurement in the range important for biofilters is surprisingly poorly developed (Devinny et al., 1999). Ideally, a conventional biofilter has a stationary water phase and a steady state microbial ecosystem, but in agricultural facilities biofilters are expected to operate under unsteady and varying load conditions due to changes in ventilation rate and variability of ammonia concentrations and other odourants. Also, possibility of the accumulation of by-products such as nitrite, nitrate, and sulfate in the biofilter medium makes water application essential for operating a biofilter in animal facilities. Therefore, the proper water application is necessary to have the optimum volume of leachate for controlling the by-product concentrations.

7.2 Ammonia Fraction in the Leachate of the Biofilters

Ammonia (NH_3) is a colourless gas at atmospheric pressure. It is lighter than air and possesses a strong penetrating odour. Microbes under aerobic and anaerobic conditions can produce it. Ammonia nitrogen exists in aqueous solutions as either the ammonium ion (NH_4^+) or free ammonia (NH_3). Ammonia dissolves readily in water (Table 7.1) where it ionizes to form the ammonium ion. Toxicity of the ammonia is much higher than the toxicity of the ammonium for fish in aqueous solutions (WHO, 1986; Metcalf and Eddy, 1991). However, the sum of two forms of ammonia is considered in terms of toxicity of wastewater.

Table 7.1 Solubility of ammonia in the water at 101 kPa (Jones (1973) and Windholz et al., (1976)

Temperature (°C)	Amount (g/L)
0	895
20	529
40	316
60	168

Theoretically, the fraction (f) of total ammonia that is non-ionized depends on both water temperature and pH, according to equations 7-1, 7-2, and 7-3 (Emerson et al., 1975):

$$f = 1/[10^{Z} + 1] \qquad (7\text{-}1)$$

Where: Z = [illegible] (7-2)

The pKa for the ammonia/ammonium equilibrium can be calculated at all temperatures, T(K), between 0 and 50°C (273<T<323) by the following equation (Emerson et al., 1975):

$$pK_a = 0.09018 + 2729.92/T \qquad (7\text{-}3)$$

Where: T = absolute temperature (K)

Thus, in water at 0°C and a pH of 6, less than 0.01% of the total ammonia present is in the non-ionized form, whereas, at 30°C and a pH of 10, 89% of total ammonia is non-ionized. In experiment 2, there were no differences between the temperatures of the biofilters. The mean temperatures for the biofilters (BF1, BF2, BF3, and BF4 were operated with 10s EBRT and 2, 20, 45, 90 ppmv ammonia, respectively) were 14.5±0.3, 15.0±0.3, 14.9±0.3, and 14.7±0.3°C.

pH values of the leachate of above biofilters with four levels of ammonia concentrations (2, 20, 45, and 90 ppmv) were different. The mean values were 7.5±0.04, 8.0±0.04, 8.3±0.04, and 8.6±0.04. With a combination of the equations 7-1, 7-2, and 7-3 and using the overall average temperature of 15°C and the above pH values, the fraction of free ammonia in the leachate of the biofilters can be predicted (Figures 7.1, and 7.2).

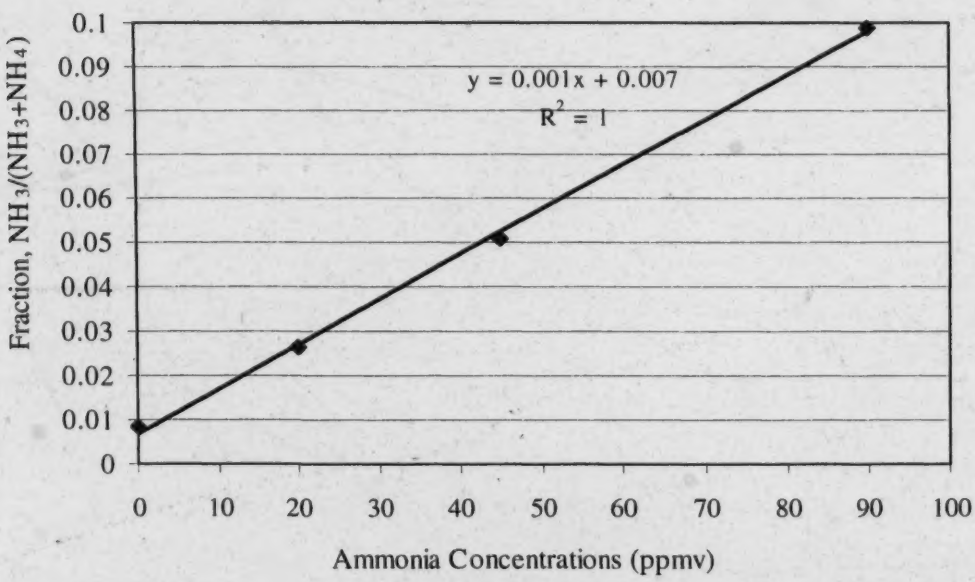


Figure 7.1 The fraction (f) of total ammonia that is non-ionized in the leachate of biofilters (Experiment 2)

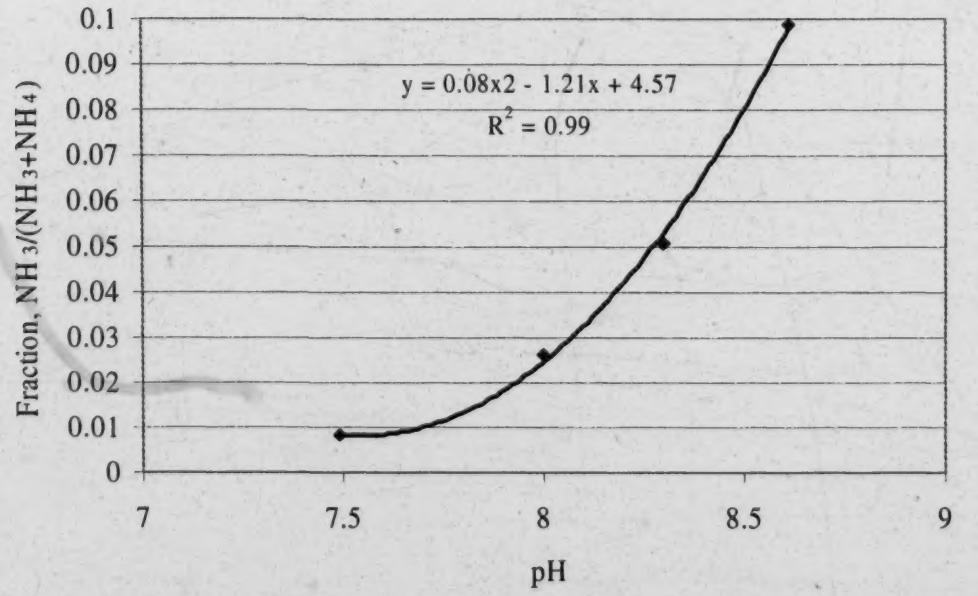


Figure 7.2 Fraction of free ammonia vs pH of the leachate of biofilters (Experiment 2)

7.3 Objectives

Based on the data results from Experiment 2, the objective was to provide a prediction model for designing water application rates for biofilters including:

1) an estimation of the amount of water needed for pre-humidification of the inlet air up to 100% based on temperature, relative humidity, and the volume of contaminated air.

2) a prediction of the amount of water required for flushing the biofilter media in order to control nutrient concentrations and by products.

7.4 Predicting the Amount of Water

Biofilter operations under unsteady state and high load conditions require two types of water application: water for increasing the relative humidity to maintain moist media; and water for controlling the concentration of leachate by-products such as nitrite and nitrate.

7.4.1 Predicting Water for Humidification:

As mentioned earlier, many researchers believe that pre humidifying the contaminated air before passing through the biofilter media is the best way to control the moisture content of the biofilter materials. For predicting the amount of water that is needed for humidification, the following factors should be considered: airflow, temperature, and RH of the contaminated air at the inlet and outlet of the biofiltration system. Table 7.2 shows the summary results of the measurement of the above factors when the biofilters were operated in the barn with four treatments of ammonia injections. It is necessary to mention that vapor pressure is temperature dependent such that an increase in temperature will increase the vapor pressure above the liquid. It is necessary to measure temperature and relative humidity very accurately.

Table 7.2 The results of the temperature and relative humidity measurement at the inlet and outlet of bioscrubber and biofilters (Experiment 2)

Trial	Temperature (°C) (Ave.±SD)			Relative Humidity (%) (Ave.±SD)		
	Scrubber (Inlet)	Scrubber (Outlet)	Biofilters (Outlet)	Scrubber (Inlet)	Scrubber (Outlet)	Biofilters (Outlet)
1	17.3±2.8	16±1.9	15.3±3.1	57.7±6.9	100	94.8±2
2	14.8±2.6	13.7±1.5	14.3±1.8	46.8±3.9	100	91.2±2
3	15.2±1.2	13.6±1.2	13.9±1.0	45.6±7.6	100	90.2±3.2
Ave.	16±2.6	14.8±2.2	14.5±1.9	50.0±8.3	100	92.1±3.1

With standard psychrometric equations (ASAE, 2003), it is possible to predict the amount of water required in the bioscrubber or humidifier stage for humidification of the air (Appendix – G).

The input data required are: 1) airflow (L/s) passing through a biofilter, 2) temperature (°C) at the inlet and outlet of biofilter, and 3) relative humidity (RH) of the air at the inlet and outlet.

$$W_1 = \frac{q \times 3600 \times 24 \times H_1}{Vsa1 \times 1000} \quad (7\text{-}7)$$

$$W_2 = \frac{q \times 3600 \times 24 \times H_2}{Vsa2 \times 1000} \quad (7\text{-}8)$$

$$W = W_2 - W_1 \quad (7\text{-}9)$$

Where:

W_1 = Volume of water available in the air at the humidifier inlet (m^3/d)

W_2 = Volume of water available in the air at the outlet of humidifier (m^3/d)

W = Volume of water used (m^3/d)

H_1 = Humidity ratio at the inlet (kg water/kg dry air)

H_2 = Humidity ratio at the outlet (kg water/kg dry air)

q = Volume of air passing through humidifier per second (m^3/s)

Vsa1 = Air specific volume at the inlet of the system (m^3/kg dry air)

Vsa2 = Air specific volume at the outlet of the system (m^3/kg dry air)

Appendix G shows the details for calculation of H_1 and H_2.

Figure 7.3 shows an example of the output of the model for the following inputs:

Temperature at the inlet (T1) =15 to 35°C

Temperature at the outlet of the bioscrubber (T2)=T1- Δt

Temperature drop (Δt) =T1-T2 = 0 or 2°C

Airflow = 80 L/s

Relative humidity of the air at the inlet of scrubber = 50%

Relative humidity of the air at the outlet of scrubber = 85 or 95%

In Chapter 8, the software developed (Appendix – H), and the necessary equations were included to the revised model (Section line 2110 to 2450) for predicting the amount of water needed for any size of biofilter.

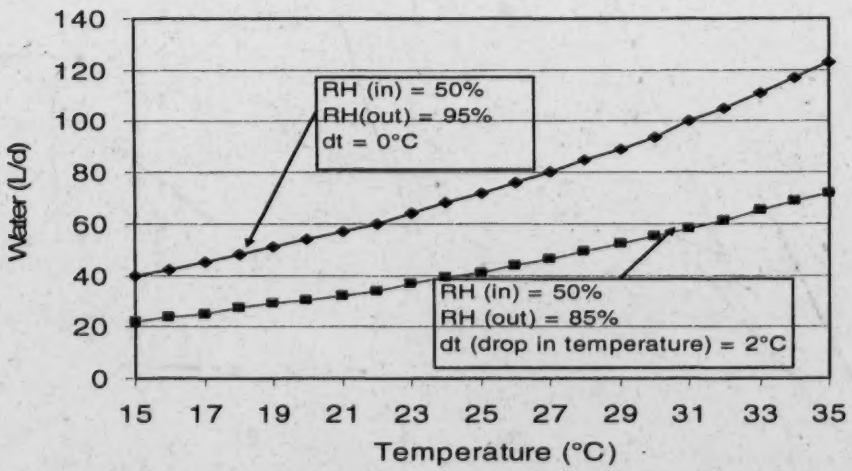


Figure 7.3 Predicting the amount of water needed per day for humidifying 80 L/s of air with 50% relative humidity

With this graph, it is possible to predict the amount of water for the 80 L/s airflow with an average relative humidity of 50%, temperature between 15 to 35°C, and outlet relative humidity between 85 to 95%.

7.4.2 Predicting the Amount of Water for Removing the By-products

Two methods of controlling the concentration of by-products and toxic materials in the biofilters are proposed as follows:

7.4.2.1 Supplying Water on the basis of Nitrite and Nitrate Concentrations in the Leachate

As mentioned in Chapter 6, four biofilters were operated in a hog barn with four levels of ammonia (2, 20, 45, and 90 ppmv). A bioscrubber was used for humidifying the air and reducing the odours, notably ammonia, before entry to the biofilters. Based on Henry's law and a limitation of ammonia diffusion in the water, the bioscrubber wasn't able to remove all the ammonia concentrations (8.7±2.8 ppmv) that were available in the barn. Thus, the biofilter without ammonia injection received an average of about 2 ppmv of ammonia throughout the experiment.

Nitrite and nitrate concentrations in the leachate from the biofilters were measured weekly during trial 1 and every two weeks through trials 2 and 3 (four 200 ml samples from daily leachates were transferred the same day to the soil science laboratory of the University of Alberta for nitrite and nitrate analyses). To determine the daily increase in leachate nitrite and nitrate concentrations between sampling days, the concentrations of the previous sample were subtracted from the concentration of the sample of the next sampling date. Figure 7.4 shows the mean nitrite and nitrate concentrations in the leachate of the biofilters.

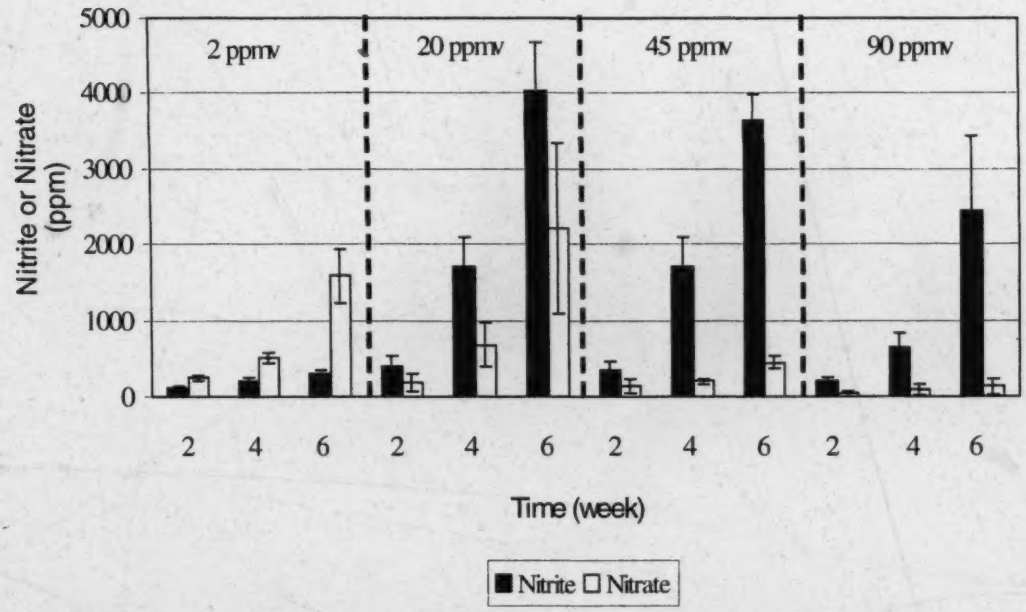


Figure 7.4 The concentrations of nitrite and nitrate in the leachate of the biofilters operated with 2, 20, 45, and 90 ppmv NH_3 (Experiment 2).

The chemical analysis (especially the measurement of the nitrite and nitrate) and measurement of volume of the leachate of the biofilters were used to determine the optimum amount of water (leachate) needed for controlling the by-products in the biofilters. The method and calculations for predicting the optimum amount of leachate needed for each biofilter will shortly be discussed. The mass of daily nitrite and nitrate nitrogen produced or washed out from each biofilter considered was based on a measurement of the concentrations of the nitrite and nitrate in the leachates of the biofilters, moisture content of the biofilters media, and bulk wet density of the media (Experiment 2). Figures, 7.5, 7.6, 7.7, and 7.8 show the overall daily production and removal of the nitrite and nitrate nitrogen in the biofilters operated with incoming 2, 20, 45, and 90 ppmv ammonia concentrations, respectively. Figure 7.9 shows the comparison of overall daily production of total NO_2^--N and NO_3^--N in the biofilters. Figure 7.10 shows the comparison of overall daily removal of total NO_2^--N and NO_3^--N from the biofilters by leachate. Figure 7.11 shows the overall average production and removal of nitrite and nitrate nitrogen together with the relevant amount of leachate. In the biofilter

with 2 ppmv ammonia concentration, the total production of nitrite and nitrate was higher than the amount flushed out until d 18 but, after this day, the accumulation of the nitrite and nitrate sharply went up to about 16 $g/m^3/d$ (Figure 7.5). Therefore, the water application of 13.40 ± 0.45 L/d in this biofilter should have been increased.

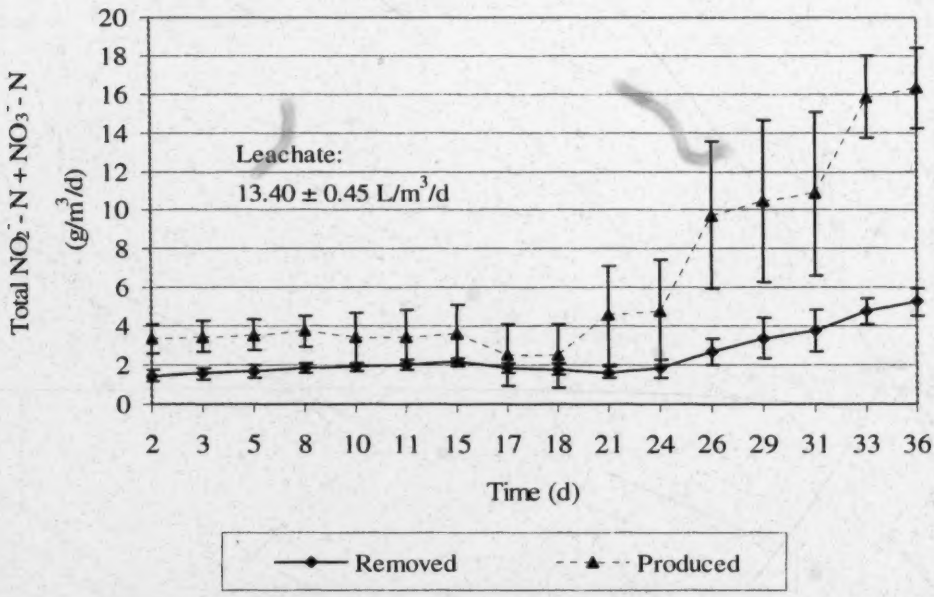


Figure 7.5 The average production and removal of total NO_2^--N and NO_3^--N from the biofilter with 2 ppmv ammonia (Experiment 2)

The biofilter injected with 20 ppmv ammonia produced the highest amount of nitrite and nitrate nitrogen in its leachate (on the average 43.1±3 $g/m^3/d$), but at d 18, the production of nitrite and nitrate nitrogen decreased to about 30 $g/m^3/d$ and then increased slowly up to 48 $g/m^3/d$ (Figure 7.6).

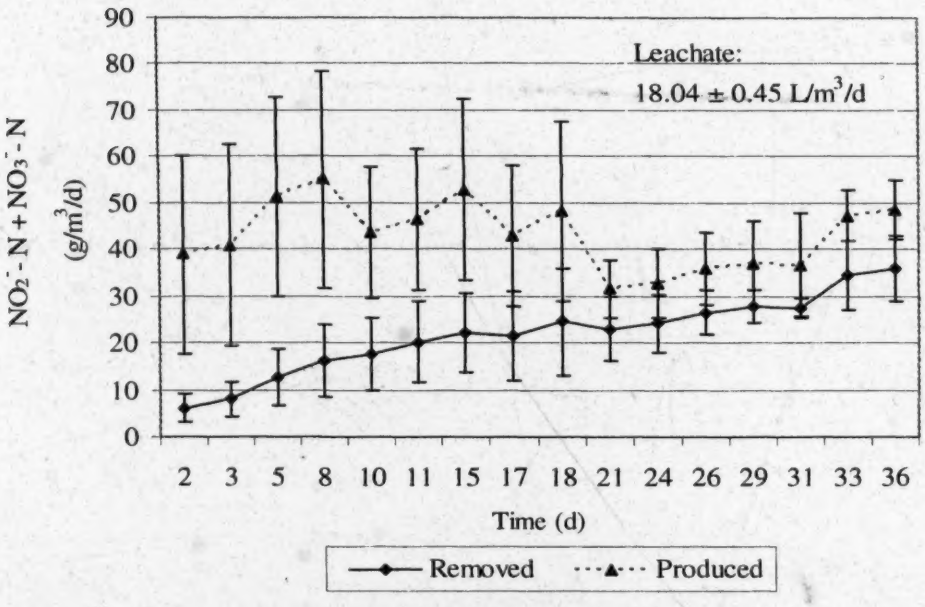


Figure 7.6 The average biofilter production and removal of total NO_2^--N and NO_3^--N with 20 ppmv ammonia (Experiment 2)

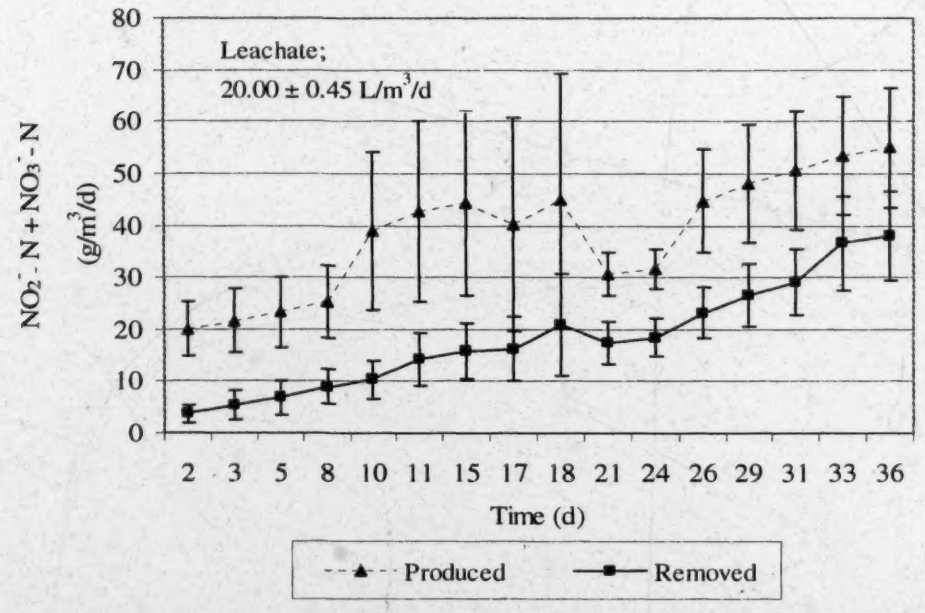


Figure 7.7 The average biofilter production and removal of total NO_2^--N and NO_3^--N with 45 ppmv ammonia (Experiment 2)

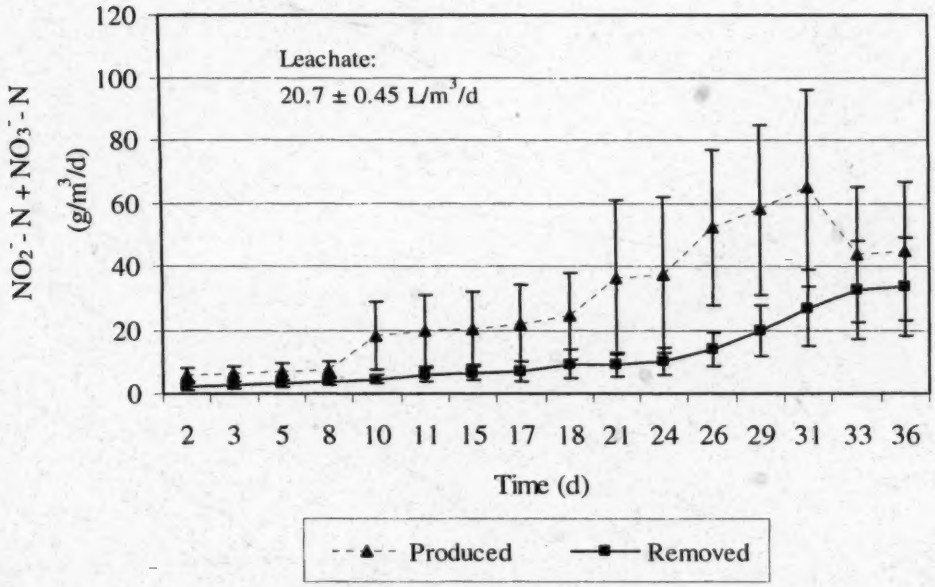


Figure 7.8 The average biofilter production and removal of NO_2^--N and NO_3^--N with 90 ppmv ammonia (Experiment 2)

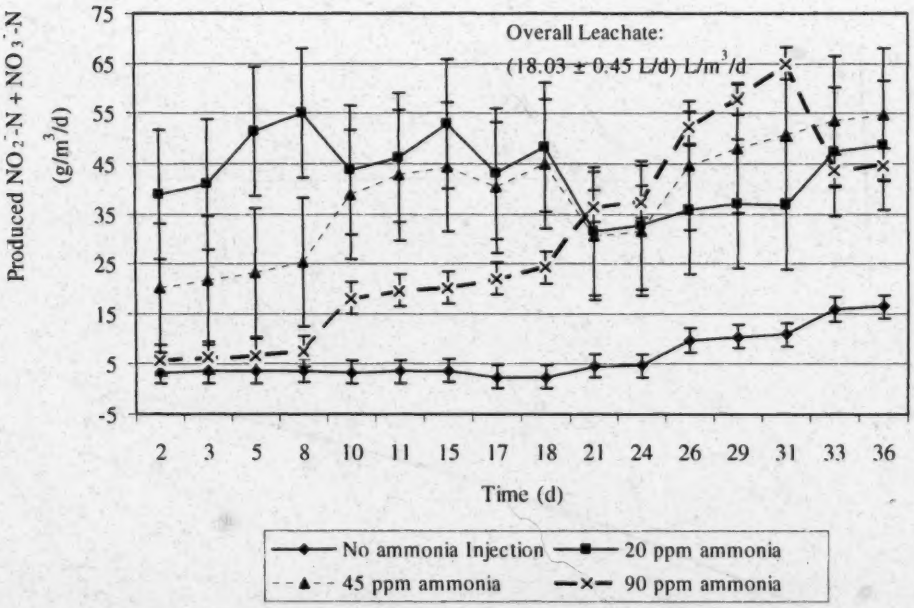


Figure 7.9 The comparison of the daily produced of total NO_2^--N and NO_3^--N in the biofilters (Experiment 2)

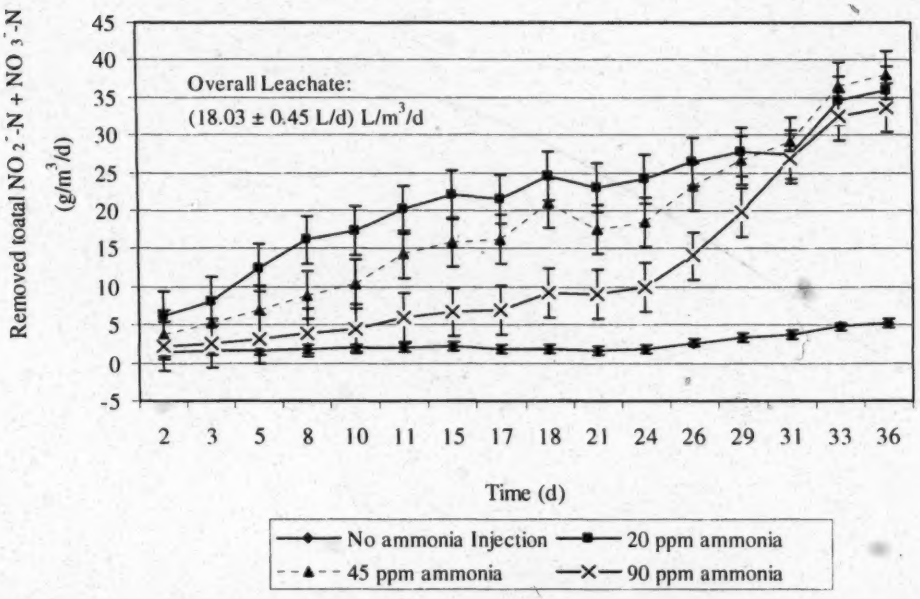


Figure 7.10 Comparison of the overall daily removed of total NO_2^--N and NO_3^--N from the biofilters by leachate (Experiment 2)

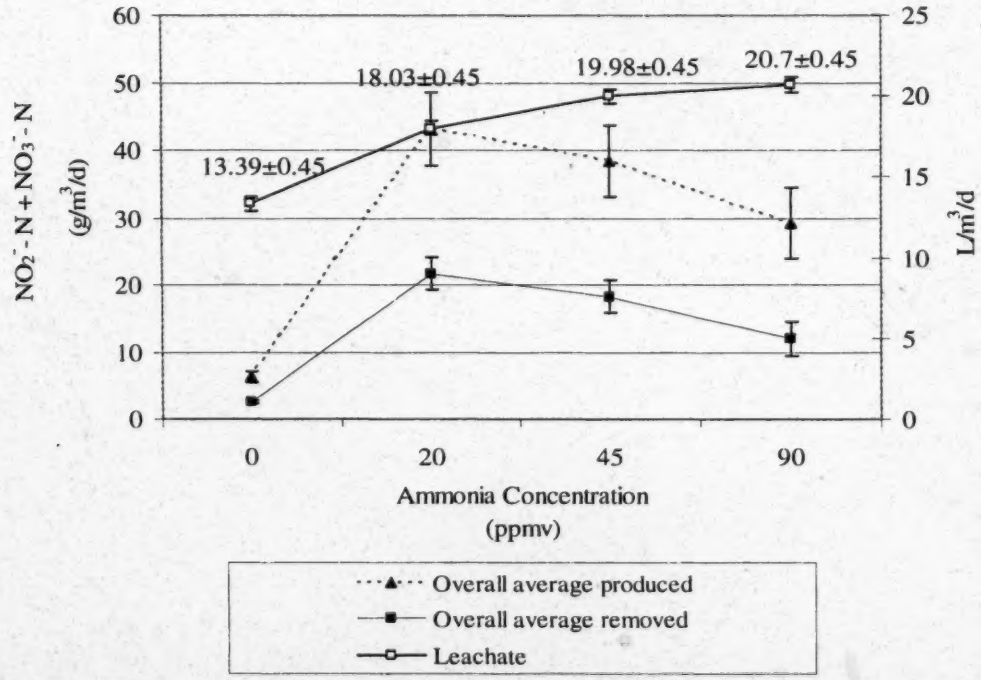


Figure 7.11 The average total NO_2^--N and NO_3^--N produced and removed per day (Experiment 2)

The daily production of nitrite and nitrate in all biofilters was higher than the daily removal of these by-products. This means that the amount of leachate, 13.39±0.45, 18.03±0.45, 19.98±0.45, and 20.7±0.45 L/m^3/d for the biofilters with 2, 20, 45, and 90 ppmv ammonia concentrations, respectively, were lower than the optimum amount of water that can be applied to the biofilters for controlling the by-product concentration. To control the concentrations of the by-products in the biofilters with different loads of ammonia concentrations, one needs to know when to add water and how much.

With the following assumptions, it should be possible to control the nitrite and nitrate in each biofilter.

a) The adjustment of the leachate water should be started when the total concentration of nitrite and nitrate in each biofilter reaches about 3,000 ppm (2,000 ppm nitrite and 1,000 ppm nitrate). This level of nitrite and nitrate was chosen because the biofilter with 20 ppmv ammonia injection showed better performance for eliminating ammonia. Moreover, Gibbons and Loehr (1998) determined that the highest treatment rates in a compost-perlite biofilter were partially limited by soluble nitrogen availability unless the concentration was 1000 mg/kg of wet bulk compost-perlite media.

b) The moisture content of the coarse compost media was measured 69%±1 on the wet basis (Appendix – I).

The total amount of water in the media is 455 L/m^3 (calculation based on 69% moisture content and density of the wet bulk media that was measured 660 kg/m^3) (Appendix – I and J) and biofilters was operated under a stationary water phase because the variation of the moisture content of the medium was negligible.

c) The concentration of the nitrite and nitrate in the leachate of the biofilters are representative of nitrite and nitrate available in the media.

d) The biofilters are fully active after 14 days of starting the operation.

Using the data provided in Table 7.2 and equations 7-14 and 7-15, we are able to predict the amount of leachate needed for removing the nutrients from each biofilter and controlling the total nitrite and nitrate concentrations at 3,000 ppm.

$$\text{Time to starting adding water (d)} = 14 + \frac{(NO_2 - N + NO_3 - N) \times V_W}{N_P - N_F} \qquad (7\text{-}14)$$

$$NO_2^-\text{-N} = \frac{2000}{1000} \times \frac{14}{46} = 0.61 \text{ g/L}$$

$$NO_3^-\text{-N} = \frac{1000}{1000} \times \frac{14}{62} = 0.22 \text{ g/L}$$

$$(NO_2^-\text{-N} + NO_3^-\text{-N}) \times d_W = N_p - N_F \qquad (7\text{-}15)$$

Where:

Vw = The total amount of water available in 1 m^3 of the wet media under operation conditions of the biofilters (L)

N_P = Total nitrite and nitrate nitrogen produced in each biofilter ($g/m^3/d$) (Table 7.3)

N_F = Total nitrite and nitrate removed from each biofilter ($g/m^3/d$) (Table 7.3)

d_W = Extra volume of leachate needed for adjusting the concentration of nitrite and nitrate at the day of operation that total concentrations of nitrite and nitrate reaches 3,000 ppm.

Based on the above formula, the amount of water and the days that the water application should be increased can be predicted as the following:

The biofilter 1 with no ammonia injection:

$$\text{Time to start adding water (d)} = 14 + \frac{(0.61+0.22)\times 455}{3.9} = 110 \text{ days}$$

Amount of water = 13.4 + d_{W1} (d_{W1} can be calculated from the Eq.7-15).

$$d_{W1} = \frac{(3.9)}{(0.61+0.22)} = 4.7 \text{ L/d}$$

It means that after about 110 days of the operation of this biofilter, it is expected that the concentration of nitrite and nitrate reaches 3,000 ppm. At this time, the total amount of leachate needed is:

Amount of leachate is needed at days 110 of the operation= 13.4+4.7 = 18.1 L/d.

A similar calculation for the other biofilters yields the data in Table 7.4. It shows the water required for controlling the nitrite and nitrate concentrations in the biofilters. In biofilter 1, the concentration of the nitrite and nitrate increased smoothly. Therefore, the sensitivity of this biofilter to the extra water application is lower than other biofilters. The ranges of water application for controlling the by-products in the biofilters with 20, 45, and 90 ppmv ammonia concentrations were calculated 18 to43.2, 20 to 44.3, and 20.7 to 41.7 $L/m^3/d$, respectively. The above ranges of water application of the biofilters operated

with more than 20 ppmv of ammonia are similar because, as mentioned in Chapter-6, there were not significant differences between their by-products (total nitrite and nitrate). However, in Chapter 8, these results will be used to predict the amount of water for different concentrations of ammonia and days of operation.

Table 7.3 Averages of accumulation $\sum NH_3$ -N (NH_3-N + NH_4^+-N), total production of NO_2^--N and NO_3^--N, total removal of NO_2^--N and NO_3^--N, and amount of leachate measured per day (Experiment 2)

Biofilters	NH_3 concentration ppmv	$\sum NH_3$-N* $g/m^3/d$	NO_2^--N + NO_3^--N produced $g/m^3/d$	NO_2^--N +NO_3^--N removed $g/m^3/d$	Leachate measured $L/m^3/d$
1	2	6.4±1.7	6.4±0.8	2.5±0.2	13.4±0.45
2	20	66.9±4.7	43.1±3.5	22.2±1.8	18.0±0.45
3	45	142.4±12.2	38.4±3	18.2±1.8	20±0.45
4	90	228.0±19.5	29.2±4.5	11.9±2.0	20.7±0.45

* Calculated from mass balance equation.

Table 7.4 The predicted range of water application based on total nitrite and nitrate production in the biofilter with 2, 20, 45, and 90 ppmv ammonia injections

Biofilters	Inlet NH_3 (ppmv)	Predicted Time (d)	Range of leachate for by-products control ($L/m^3/d$)
1	2	110	13.4 to 18.1
2	20	32	18.0 to 43.2
3	45	33	20.0 to 44.3
4	90	36	20.7 to 41.7

7.4.2.2 Supplying Water on the basis of Electrical Conductivity

The measurement of the electrical conductivity of the leachate of the biofilter could be a good and practical method that can help in controlling the by-products in the biofilters. With the assumption that the dominant by-products of the biofilter are nitrite and nitrate, it should be possible to determine the optimum range of electrical conductivity needed for the biofilter operator to be able to adjust the water application to a certain level.

After Trial 3, for three weeks the biofilters were operated and the above parameters were measured. Figure 7.12 shows that by increasing the amount of water application in different biofilters, the electrical conductivity of the leachate of each biofilter can be adjusted.

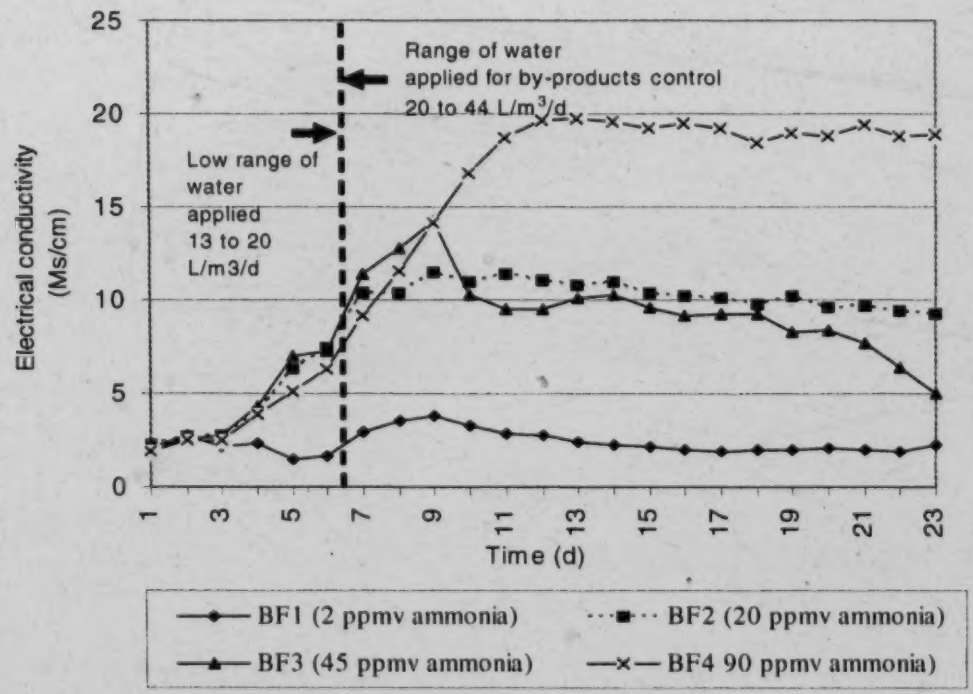

Range of water applied for by-products control 20 to 44 L/m3/d
Low range of water applied 13 to 20 L/m3/d
Electrical conductivity (Ms/cm)
Time (d)
BF1 (2 ppmv ammonia)
BF2 (20 ppmv ammonia)
BF3 (45 ppmv ammonia)
BF4 90 ppmv ammonia)

Figure 7.12 Electrical conductivity of the leachate of the biofilters were operated with two ranges of water applications

Table 7.5 shows the summary results of the measurements of electrical conductivity and total nitrite and nitrate concentrations of the leachates of the biofilters. In the leachate of the biofilter with 2 ppmv ammonia concentration, total nitrite and nitrate nitrogen

increased from 309±55 to 1624±63 ppm. Meanwhile, the electrical conductivity increased from 1.5 to 4 ms/cm (Figure 7.13). This means that at day 42 of operation, the concentration of nitrite and nitrate still was not high, and 13.4±0.45 $L/m^3/d$ water applications was enough. However, the nitrification process is limited in this biofilter by ammonia nitrogen load. At the end of trials, higher elimination capacity was measured in this biofilter. Thus, the electrical conductivity of the leachate decreased before increasing the water application.

Total nitrite and nitrate concentration in the leachate of biofilter 2 with 20 ppmv ammonia injection increased from 438±209 ppm to 5,020±280 ppm and electrical conductivity increased from 2 to 11 ms/cm (Figure 7.14). The water application increased at day 11, and electrical conductivity decreased slowly. Before increasing the water application, the electrical conductivity was stabilized because at high concentration of the by-products the sensitivity of the biofilter to water application seems to be higher and a small change in applied water application can rapidly wash out the by-products. However, the required increase in water application can be found from above (18.04±0.45 to about 35 $L/m^3/d$). The optimum level of the electrical conductivity seems to be between 6 to 8 ms/cm because in this range, better performance of the biofilters was recognized. In biofilters 3 with 45 ppmv ammonia, the increase in total nitrite and nitrate concentration and the electrical conductivity is very similar to the biofilter 2 with 20 ppmv ammonia injection. The only difference was that the total nitrite and nitrate were not the dominant by-products. The ammonium (NH_4^+) is probably dominant in the leachate of this biofilter (Chapter 8 nitrogen mass balance results). However, Figure 7.15 shows how the electrical conductivity of the leachate of this biofilter was adjusted by increasing water application from 20±0.45 to 40 $L/m^3/d$. In biofilter 4 with 90ppmv ammonia injection, nitrite produced from 156±22 to 2,862±912 ppm and electrical conductivity changed from 2 to 20. Figure 7.16 shows the adjustment of the electrical conductivity of the leachate of this biofilter by increasing the amount of water application.

Table 7.5 Summary of total nitrite, nitrate, and electrical conductivity of the leachate of the biofilters with different concentrations of ammonia (Experiment 2)

Biofilters	Days of operation	$NO_2^- + NO_3^-$ (ppm) Ave.±SD	Range of Electrical Conductivity (Ms/cm)
No ammonia	14	309 ± 55	1.5 to 4
	28	664 ± 19	
	42	1,624 ± 63	
20 ppmv	14	438 ± 209	2 to 11
	28	2,508 ± 145	
	42	5,020 ± 280	
45 ppmv	14	458 ± 112	2 to 14
	28	2,040 ± 477	
	42	4,258 ± 721	
90 ppmv	14	156 ± 22	2 to 20
	28	583 ± 182	
	42	2,862 ± 912	

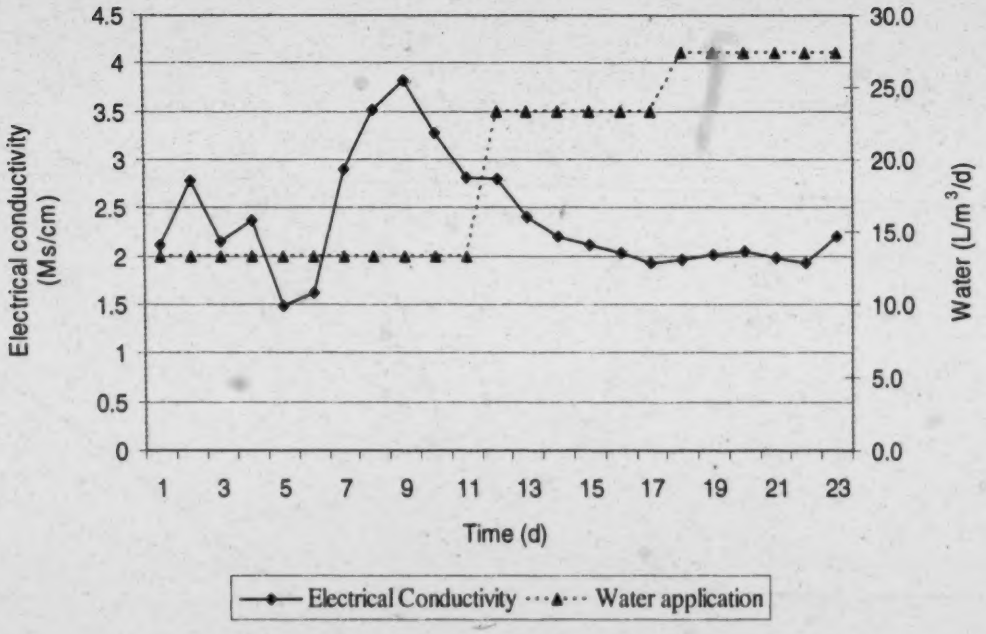


Figure 7.13 The effect of water application on electrical conductivity of biofilter with no ammonia

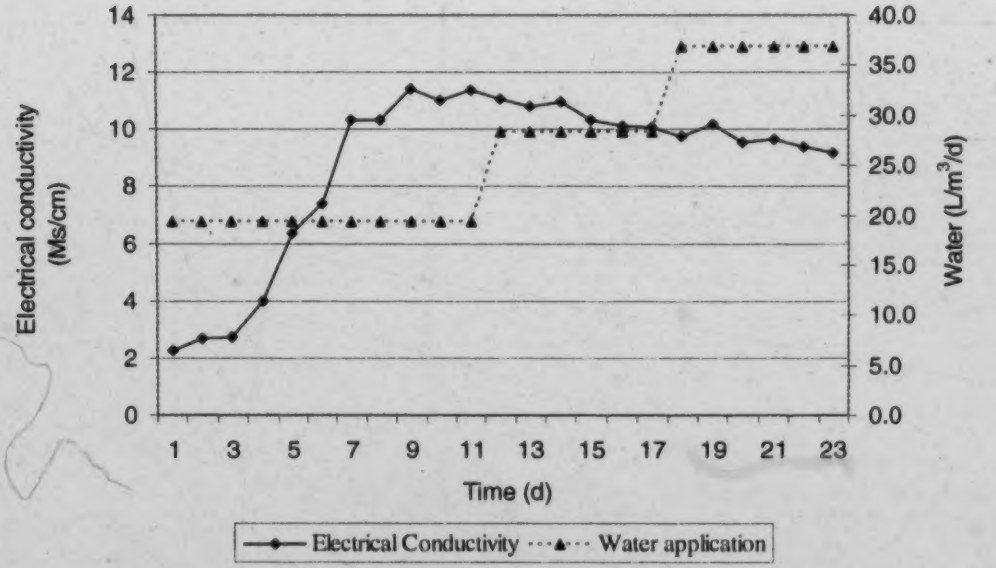


Figure 7.14 The effect of water application on electrical conductivity of the biofilter with 20 ppmv ammonia

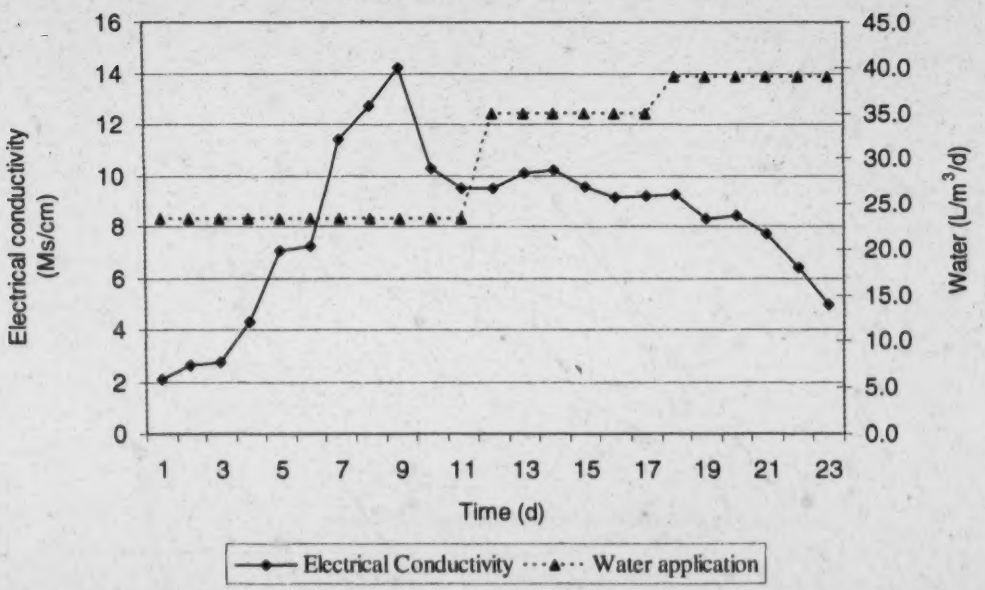


Figure 7.15 The effect of water application on electrical conductivity of the biofilter with 45 ppmv ammonia

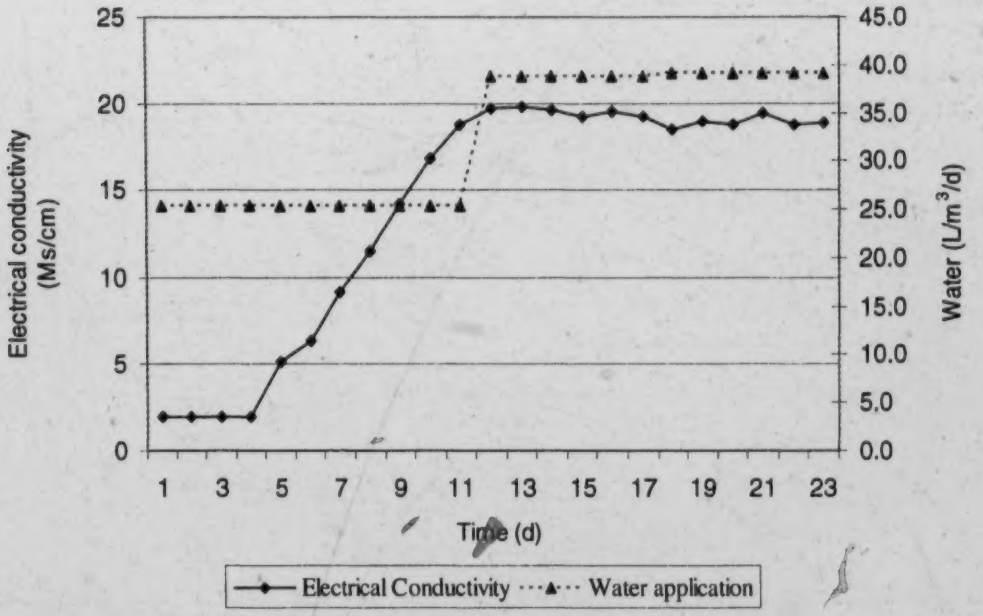


Figure 7.16 The effect of water application on electrical conductivity in biofilter with 90 ppmv ammonia

7.5 Conclusions

The following conclusions were drawn:

1. The leachate in the bioflters (BF1, BF2, BF3, and BF4) operated with 2, 20, 45, and 90 ppmv ammonia were 13±0.45, 18±0.45, 20±0.45, and 21±0.45 L/m3/d, respectively.

2. Under the conditions of this experiment (temperature, RH, and airflow), the volume of water required for humidifying the 80 L/s contaminated air was predicted to be in the range of 32 to 67 L/d for the temperature range 15 to 25°C.

3. The total nitrite and nitrate concentrations in the leachate from the biofilter operated with about 2 ppmv of ammonia concentration should reach about 3,000 ppm after 110 days of operation. The range of leachate needed for removing the by-products was 13.4±0.45 to 18.1 $L/m^3/d$.

4. The total concentrations of nitrite and nitrate from the biofilters that operated with 20, 45 and 90 ppmv ammonia reached 3,000 ppm after 32 to 36 days of operation. The range of leachate needed for removing the by-products is 18±0.45 to 44 $L/m^3/d$.

5. Under the conditions of this experiment, the optimum range of the electrical conductivity was found to be about 6 to 8 ms/cm.

6. Electrical conductivity can be used as a measure of water application for controlling by-product concentration.

7.6 References

American Society of Agricultural Engineers (ASAE), 2003. ASAE STANDARDS 2003, 50 th Anniversary Edition. St. Joseph, MI: USA. Adupted and published by:ASAE.

Bohn, H.L. 1975. Soil and compost filters of malodorant gases. Journal of the Air Pollution Control Association 25(9): 953-955.

Corsi, R. and L.P. Seed. 1995. Biofiltration of BTEX: effects of media, multiple substrates, and dynamic mass loadings. Air and Waste Management Association, 88th Annual meeting and Exhibition, San Antonio, Texas, June 19-23.

De Heyder, b., A. Overmeire, H. Van Langenhove, and W. Verstraete. 1994. Biological treatment of waste gas containing the poorly water-soluble compound ethane using a dry granular activated carbon biobed. VDI Berichte Nr. 1104. 301-311.

Devinny, J. S., Deshusses, M.A., and Webster, T. S. 1999. Biofilteration for air pollution control. Lewis Publishers, New York, USA.

Emerson, K., Russo, R.C., Lund, R.E., & Thurston, R.V. 1975. Aqueous ammonia equilibrium calculations: effect of pH and temperature. J. Fish. Res. Board Can., 32: 2379-2383.

Gibons, M.J. and Loehr, R.C., 1998. Effect of media nitrogen concentration on biofilter performance, J. Air Waste Manage. Assoc., 48(3), 475.

Jones, K. 1973. Ammonia. In: Bailar, J.C., Jr, Emeleus, H.J., Nyholm, R., & Trotman-Dickenson, A.F., ed. Comprehensive inorganic chemistry, New York, Pergammon Press, Vol. 2, pp. 199-227.

Leson, G., and Winer, A. M. 1991. Biofiltration: an innovative air pollution control technology for VOC emissions. Air & Waste Management Association 41(8):1045-1054.

Metcalf and Eddy Inc., 1991. Wastewater engineering: Treatment, disposal, and reuse (3rd edition). McGraw-Hill, Inc. New York. NY.

Ottengraf, S.P., 1986. Exhaust gas purification. In: Biotechnology, Vol. 8. Eds. H.J. Rehm and G. Reed. VCH, Weinheim, FRG. pp: 427-452.

Swanson, W. J. and R. C. Loehr. 1997. Biofiltration: fundamentals, design and operations principles, and applications J. Environ. Eng., 123(6): 538-546.

Van Lith, C., G. Leson and R. Michelson, 1997. Evaluating design options for biofilter. J. Air & Waste Manage. Assoc., 47: 37-48.

Williams, T.O., F.C. Miller, 1992. Biofilters and facility operations. BioCycle 33: 75-79.

Windholz, M., Budavari, S., Stroumtsos, L.Y., & Fertig, M.N., eds. 1976. Merck Index, Merck and Co. Inc, 9th ed., Rahway, New Jersey, p. 69.

World Health Organization (WHO), 1986. Environmental Health Criteria 54. Ammonia. Accessed online at http://www.inchem.org/documents/ehc/ehc 54.htm on 2003/05/16.

8. NITROGEN MASS BALANCE AND MODEL PREDICTION OF BIOFILTER PERFORMANCE

8.1 Introduction

The major purpose of environmental models is to predict the impact of various loading scenarios or management alternatives. In spite of monitoring data availability, biofilters must be modeled under different conditions. A simple mass balance based on the principle of continuity (matter is neither created nor destroyed in macroscopic chemical, physical, and biological processes) can be used to model aquatic chemical systems (Devinny et al. 1999; Schnoor, 1996).

The fate of chemicals is determined in the aquatic environment by two factors: their reactivity, and the rate of their physical transport through the environment. Basically, the key elements in a mass balance evaluation are a clearly defined control volume, a knowledge of inputs and outputs that cross the boundary of the control volume, a knowledge of the transport characteristics within the control volume and across its boundaries, and a knowledge of the reaction kinetics within the control volume (Schnoor, 1996).

As mentioned earlier, many physical and chemical process factors influence the performance and long-term stability of biofilters for air pollution control. Although choosing the right media in terms of having low pressure drop, absorbability of water, and microorganisms is essential for biofilter operation, the four most important parameters for an efficient biofilter are medium moisture content, pH, bed temperature, and the contaminant loading to the biofilter. Other factors are also important, but they influence medium lifetime or removal performance to a lesser extent than do these four factors (Devinny et al. 1999). Biofilter operators must ensure the continuing availability of nutrients during operation. Ideally, a biofilter has a stationary water phase and a steady- state microbial ecosystem so it might be expected that the nutrient content can be maintained and continually recycled. Degradation of the biomass releases the nutrients in soluble form, where growing cells can take them up again. However, biofilters can produce leachate, either intentionally or inadvertently, and this will carry dissolved nutrients out of the biofilter. Gibbons and Loehr (1998) determine that the highest treatment rates in a compost-perlite biofilter are partially limited by soluble nitrogen

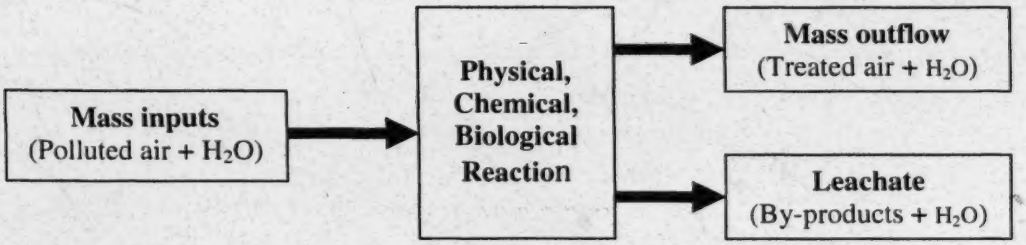
availability unless the concentration was 1,000 mg kg^{-1} of the above bulk wet media. Also, the nitrogen-to-carbon ratio should be at least 1 to 100. However, the fundamental means of biofiltration is the action of pollutant degrading microorganisms. This means that controlling operational parameters in a biofilter is an attempt to control the activity of their process.

Beginning with the early development of biofilters, efforts have been directed toward modeling. The objectives were to organize experimental data and to understand simple relationships between parameters such as media surface area, biological activity, biofilm thickness, and pollutant removal. In addition, a real interest exists in biofilter modeling for design purposes such as being able to predict the performance of a biofilter under the given conditions. Finally, biofilter models can also be used for process optimization (Devinny et al. 1999).

The main goal of this chapter is to revise the model that was developed in section 2.8.9 based on the results of the experiments and literature references with the following objectives:

a) To predict the amount of water needed for humidifying the incoming contaminated air based on temperature (°C), airflow (L/s), and relative humidity (RE) of the air at the inlet and outlet of that biofilter.
b) To predict the amount of leachate needed to control the concentrations of by-products (nitrite and nitrate) in the media.
c) To predict the minimum volume of medium (coarse compost) and empty bed retention time (EBRT) needed for a biofilter based on ammonia concentration in the contaminated air and the amount of nitrite and nitrate that can be produced in the biofilter.
d) To predict the elimination capacity (EC), removal efficiency (RE), and pH of the leachate of the biofilters under experimental conditions.

However, Figure 8.1 shows a mass balance evaluation of the biofilters.



Control volume
(Biofilter)

Figure 8.1 The schematic diagram of the mass balance modeling approach to the solution of mass transport problems and chemical reactions (Schnoor, 1996)

8.2 Reaction and Possible Transformation

A consecutive reaction can be used to describe the bacterial nitrification of ammonia. In the first step of nitrification, ammonia is oxidized by *Nitrosomonas* sp. to nitrite. Then, in the second step, nitrite is oxidized by *Nitrobacter* sp. to nitrate. Approximate equations for the reactions that occur are equations 8-1 and 8-2. The rate of oxygen demand is about 4.3 mg O_2 per mg of ammonia-nitrogen that is oxidized to nitrate-nitrogen. Moreover, 8.64 mg HCO_3^- per mg of ammonia-nitrogen is neutralised. The growth and activity of these organisms can be inhibited by a variety of organic and inorganic agents such as high concentrations of ammonia and nitrous acid. The effect of pH is also significant. Temperature of the air pass through a biofiltration system has a tremendous influence on the growth and activity of nitrifying bacteria. Dissolved oxygen concentrations above 1 mg/L are essential for nitrification to occur. The nitrification slows down or ceases if the dissolved oxygen levels drop below this value (Metcalf and Eddy, 1991). However, Figure 8.2 shows the possible transformation of the nitrogen in the biofilters.

$$55\ NH_4^+ + 76\ O_2 + 109\ HCO_3^- \longrightarrow C_5H_7O_2N + 54\ NO_2^- + 57\ H_2O + 104\ H_2CO_3 \quad (8\text{-}1)$$

$$400\ NO_2^- + NH_4^+ + 4\ H_2CO_3 + HCO_3^- + 195\ O_2 \longrightarrow C_5H_7O_2N + 3\ H_2O + 400\ NO_3^- \quad (8\text{-}2)$$

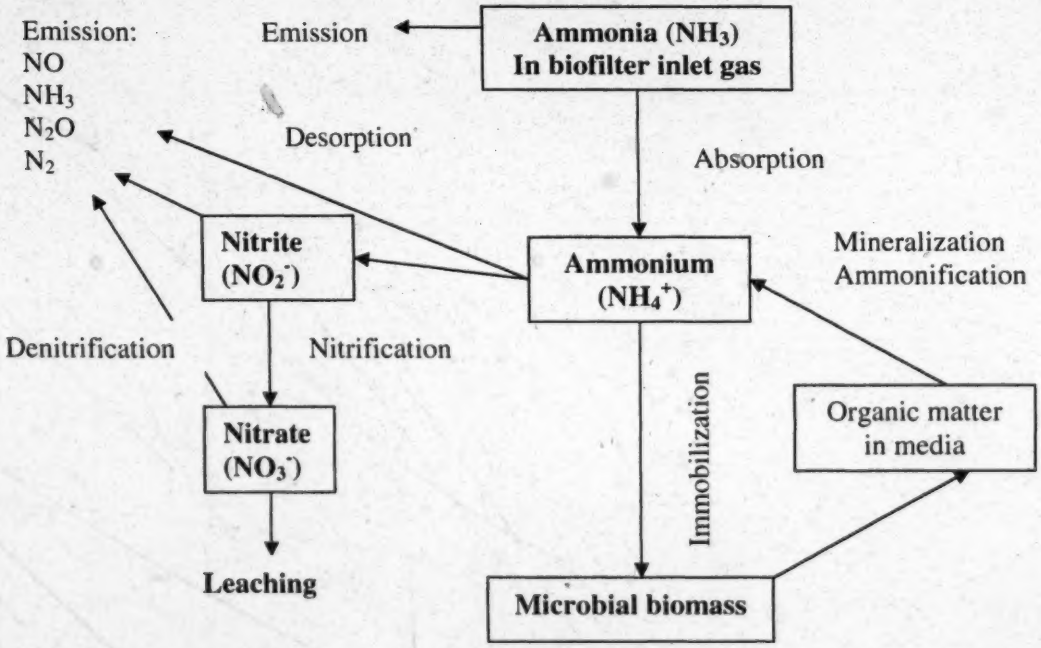


Figure 8.2 Possible nitrogen transformations in biofilters (modified from Sun et al.2000; Metcalf and Eddy, 1991; Brady, 1990)

8.3 Nitrogen Mass Balance in Biofilters

The mass balance evaluation is a method to evaluate biofilter performance quantitatively. It focuses not only on the mass of materials ($g/m^3/d$) that enter or leave the biofilter by air but also considers the mass of by-products that are produced or removed from the biofilter by leachate. Ammonia nitrogen can be removed or transformed by assimilation, nitrification or denitrification in the aquatic environment. Nitrification is the first step in the removal of nitrogen by the nitrification-denitrification process. Figure 8.3 shows the pathway of nitrogen removal in the aquatic environment. In this analysis, the main focus is on the nitrification and stabilization of the ammonia nitrogen.

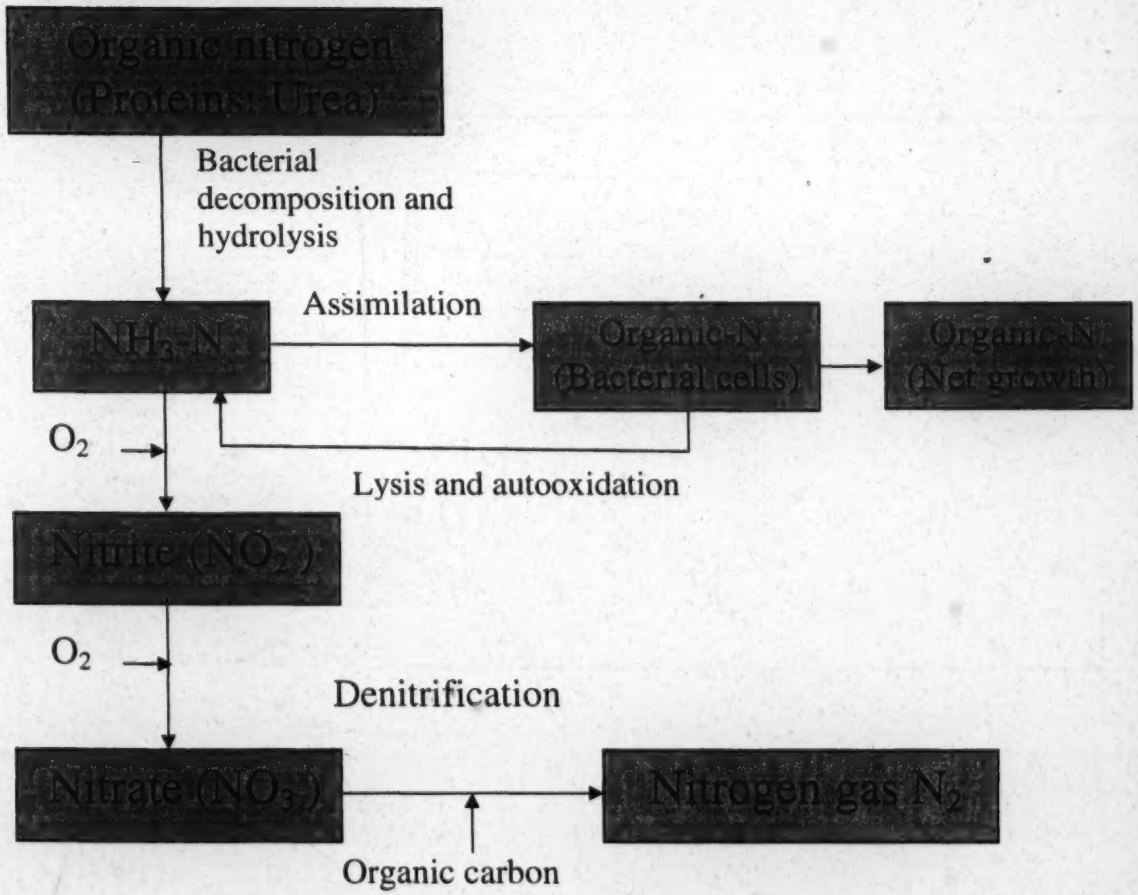


Figure 8.3 The pathway of nitrogen removal through assimilation or the nitrification-denitrification process (adapteded from Medcalf and Eddy 1993)

Many factors or parameters should be measured for mass balance evaluation. However, the main factors that have been measured in terms of the overall mass balance evaluation include ammonia concentrations at the inlet and outlet of each biofilter (C_{gi} and C_{go}), airflow (Q), temperature, the volume of daily leachate, and the nitrite and nitrate concentrations of the leachate. The volume of the media for each biofilter was 0.15 m^3, moisture content (MC) of the media measured 69%±1 of the wet material, and the density of the wet material measured 660 kg/m^3 (Appendix I, and J). As a result, assuming that:

1) Biofilters operate with a stationary water phase and at steady state conditions (assimilation = lysis and autooxidation)

2) Leachate from a biofilter is representative of the liquid within that biofilter

3) Denitrification is negligible in the biofilter liquid

4) Production of ammonia in the biofilter = 0

Then, the overall mass balance of N can be represented by:

NH_3-N (in) – NH_3-N (out) =

$$\Sigma(NO_2^-\text{-N}) + \Sigma(NO_3^-\text{-N}) + \Sigma(\text{dissolved } NH_3\text{-N} + NH_4^+\text{-N}) \quad (8\text{-}3)$$

Where:

NH_3-N (in) = total mass of ammonia nitrogen that enter a biofilter daily ($g/m^3/d$),

NH_3-N (out) = total mass of ammonia that went out from a biofilter daily ($g/m^3/d$),

$\Sigma(NO_2^-\text{-N})$ = total daily nitrite nitrogen production in each biofilter ($g/m^3/d$),

$\Sigma(NO_3^-\text{-N})$ = total daily nitrate nitrogen production in each biofilter ($g/m^3/d$), and

$\Sigma(\text{dissolved } NH_3\text{-N} + NH_4^+\text{-N})$ = assumed to accumulate ($g/m^3/d$).

$$NH_3\text{-N (in)} = \frac{V \times C_{gi}}{10^6 \times V_1} \times \frac{14}{17} \div V_{bm} \quad (8\text{-}4)$$

$$NH_3\text{-N (out)} = \frac{V \times C_{go}}{10^6 \times V_1} \times \frac{14}{17} \div V_{bm} \quad (8\text{-}5)$$

$$V = Q \times (86400 s/d) \quad (8\text{-}6)$$

$$V_1 = \frac{mRT}{P} \times \frac{28.32}{17 \times 453} = \frac{(1)(0.730)(492 + 1.8T_1)}{(1)(272.12)} \quad \text{(Haug, 1993)} \quad (8\text{-}7)$$

Where:

C_{gi} = concentration of ammonia at the inlet of biofilters (ppmv),

C_{go} = concentration of ammonia at the outlet of biofilters (ppmv),

V = the volume of the contaminated air entering a biofilter (L/d),

V_1 = the volume of 1 g of gas (ammonia) (L) at temperature T1 (°C) of contaminated air,

Q = average airflow (L/s) = 19L/s,

m = 1 g ammonia gas,

P = 1 atmospheric pressure,

R = 0.730 (the universal gas constant),

T = absolute temperature = $492 + 1.8T_1$,

T_1 = average temperature of the gas or air at the inlet and outlet of a biofilter (°C), and

V_{bm} = volume of biofilter material = 0.15 (m^3).

Elimination capacity (*EC*) is a normalized factor or the mass of contaminant that is degraded per unit volume of filter media per unit of time (equation 8-8). Evaluation of the *EC* of a biofilter allows comparison of the performance of that biofilter to other biofilters. Typical units for elimination capacity are $g/m^3/h$, but in this experiment, the unit chosen is $g/m^3/d$. The EC can be calculated as follows:

$$EC = \frac{V(C_{gi} - C_{go})}{V_1 \times 10^6} \times \frac{14}{17} + V_{bm} \qquad (8\text{-}8)$$

Where:

EC = Elimination capacity ($g/m^3/d$) is the quantity of ammonia nitrogen that can be absorbed daily by 1 m^3 of the media.

8.3.1 Measurement of NO_2^--N and NO_3^--N and Overall Mass Balance in the Biofilters

Nitrite and nitrate concentrations in the leachate from the biofilters were measured biweekly (Experiment 2). The daily increase in leachate nitrite and nitrate concentrations between sampling days was determined by subtracting the concentrations of the days before and after that particular test day. That number was divided by the interval (14 days). The biofilter system is assumed to have a stationary water phase, and the leachate of each biofilter is assumed to be representative of its liquid contents. In order to calculate daily nitrate and nitrite concentrations produced or removed from the biofilters, the amounts of leachate were measured five days per week. Furthermore, the density of wet media (660 kg/m^3) and the moisture content (69%) were measured. Based on the stated assumptions and the described calculations, the nitrite and nitrate quantities produced in the biofilters are calculated based on the equations 8-9 and 8-10:

$$\Sigma(NO_2^- - N) = \frac{(C_2 - C_1) \times V_w}{d \times V_{bm} \times 10^3} \times \frac{14}{46} + \frac{(C_2) \times V_t}{V_{bm} \times 10^3} \times \frac{14}{46} \qquad (8\text{-}9)$$

$$\sum(NO_3^- - N) = \frac{(C_4 - C_3)\times V_w}{d \times V_{bm} \times 10^3} \times \frac{14}{62} + \frac{(C_4)\times V_l}{V_{bm} \times 10^3} \times \frac{14}{62} \quad (8\text{-}10)$$

Where:

C_1 = Concentration of nitrite (ppm) in the leachate at the first sampling,

C_2 = Concentration of nitrite (ppm) in the leachate the next day,

C_3 = Concentration of nitrate (ppm) in the leachate at the first sampling,

C_4 = Concentration of nitrate (ppm) in the leachate the next day,

V_w = The volume of water exist in 0.15 m^3 of the media (68 L). It is calculated based moisture content (0.69%) and measured wet density of the media (660 kg/m^3),

V_l = Average volume of the leachate (L/d) between two sampling the leachate for lab tests, and

d = Number of days between two measurements of the leachate.

The overall results of this analysis are presented in Figures 8.4 to 8.7, and Figure 8.8. Tables 8.1 and 8.2 show the summary of the mass balance throughout the experiment. The nitrogen mass balance conducted for the biofilters in each trial is presented in Appedix - F. As mentioned in Chapter 6, biofilters 1, 2, 3, and 4 were operated at 1.9±0.4, 21.0±0.7, 46.8±1.5, and 87.5±2.0 ppmv ammonia concentrations, respectively. The parameters of nitrogen mass balance from both sides of the equation 8-3 are NH_3-N (in), NH_3-N (out), $\sum(NO_2^-N)$, $\sum(NO_3^-N)$, and $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$.

The nitrification processes in biofilter 1 took place with the production and accumulation of nitrite and nitrate in the liquid (Figure 8.4). The parameters of mass balance (equation 8-3) from left to right for this biofilter were calculated to be 12.5±2.6, 0.9±0.5, 1.9±0.2, 6.6±1.2, and 3.1±2.9 $g/m^3/d$, respectively. There are high variations of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ and NH_3-N (in) because of the variation of ammonia concentration in the barn. It seems ammonia dissolves in the biofilter liquid and gradually eliminates to nitrite and nitrate. However, the rate of the transformation of ammonia nitrogen to nitrite and nitrate nitrogen (R_N) can be calculated by:

$$R_N = \frac{(NO_2^- - N) + (NO_3^- - N)}{(NH_3 - N(in)) - (NH_3 - N(out))} \times 100 \quad (8\text{-}11)$$

Since the factors NH_3-N (in) and NH_3-N (out) are normalized per m^3 of the biofilter media, R_N is equivalent to:

$$R_N = \frac{(NO_2^- - N) + (NO_3^- - N)}{(EC)} \times 100 \qquad (8\text{-}12)$$

However, R_N of biofilter 1 with no ammonia injection was 73% and the rate of total accumulation or washing out of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ was 27%. A large portion of the right side of the mass balance equation was measured in the form of total nitrite and nitrate nitrogen (8.6±1.5 $g/m^3/d$) and just 3.1±2.9 $g/m^3/d$ nitrogen are available in the form of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$. It is interesting to note that in biofilter 1, the amount of daily $\sum(NO_2^-\text{-}N + NO_3^-\text{-}N)$ that washed out (3.2±0.4 $g/m^3/d$) was close to the total amount of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$. There is a possibility that the daily production of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ washed out with other by-products instead of accumulating in the biofilter. As a result, the operation of this biofilter was limited to the availability of ammonia in the biofilter. However, the accumulation of $\sum(NO_2^-\text{-}N + NO_3^-\text{-}N)$ can be dominant relative to the accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$. By increasing the water application to control the nitrite and nitrate concentrations, dissolved ammonia and ammonium in the liquid should not be maintained.

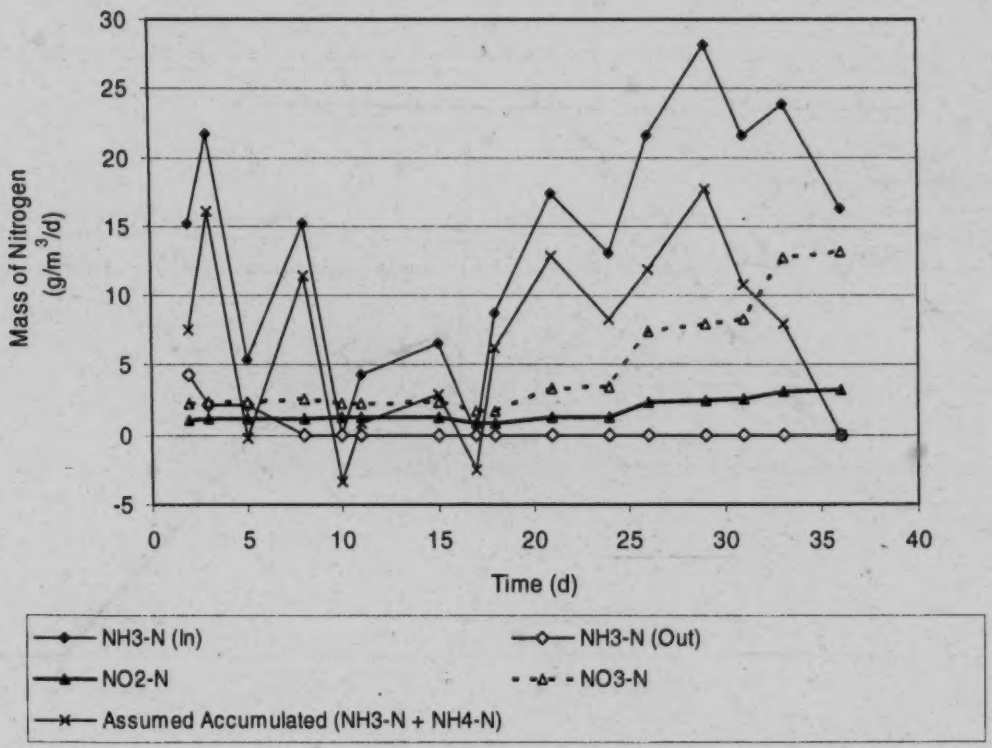


Figure 8.4 Overall mass balance of nitrogen in biofilter 1 (2 ppmv)

For biofilter 2 (20 ppmv), the parameters of nitrogen mass balance (equation 8-3) from the left to the right side were 139.6±4.6, 28.2±3.4, 30.4±4.4, 11.7±1.5, and 70.6±5.9 $g/m^3/d$. This biofilter had the highest rate of nitrification or production of $\sum(NO_2^-\text{-}N + NO_3^-\text{-}N)$. Approximately 38% of the EC was eliminated as nitrite and nitrate nitrogen. However, $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ accumulated in the liquid. About 62% of the EC of this biofilter was accumulated in the form of ammonia and ammonium in the liquid (Figure 8.5). Thus, we can conclude: a) this biofilter was operated with high rate of nitrification because there was not any limitation of ammonia accessibility for the nitrification processes, and b) increasing the rate of water application for increasing the leachate from 18.5±0.5 $L/m^3/d$ to 44 $L/m^3/d$ is essential to maintaining acceptable nitrite and nitrate levels.

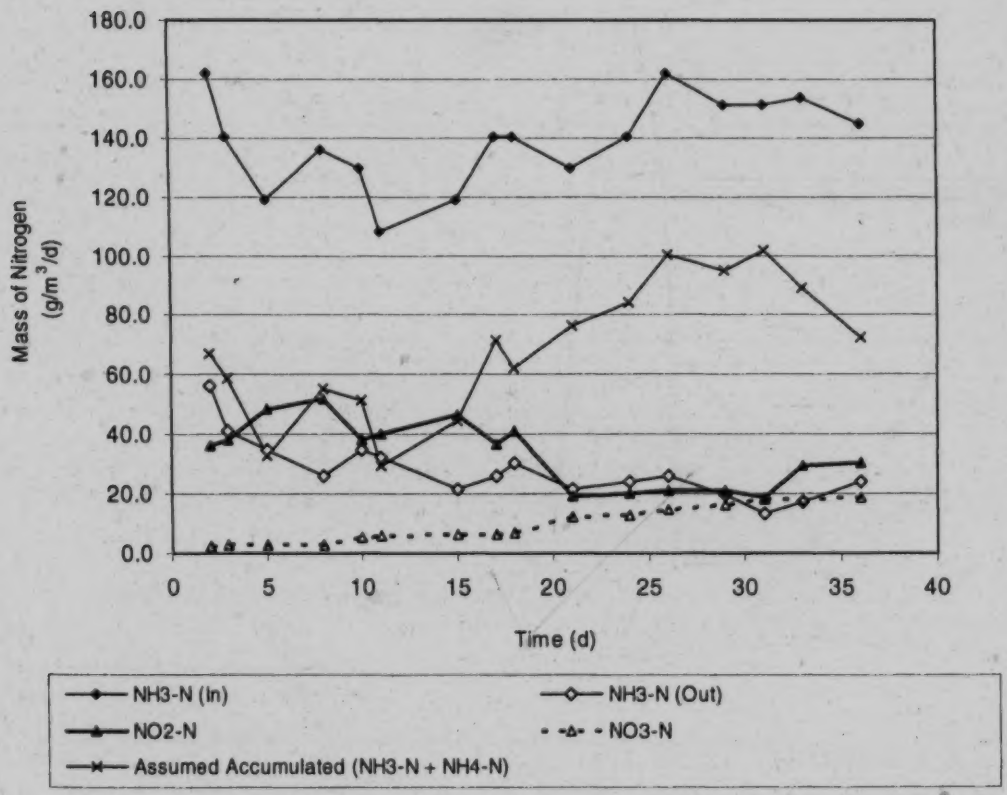


Figure 8.5 Overall mass balance of nitrogen in the biofilter 2 (20 ppmv)

For biofilter 3 (45 ppmv) the above mass balance factors were 302.9±9.6, 119.9±10.5, 37.9±3.7, 2.9±0.4, and 143.4±10.5 $g/m^3/d$, respectively. The rate of nitrification of this biofilter was 22% of the EC eliminated to nitrite and nitrate nitrogen (Figure 8.6). The accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ was dominant (78% of the EC). The rate of nitrate nitrogen production (2.9±0.4 $g/m^3/d$) decreased in this biofilter. This is probably due to the accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ or $\sum NO_2^-\text{-}N$.

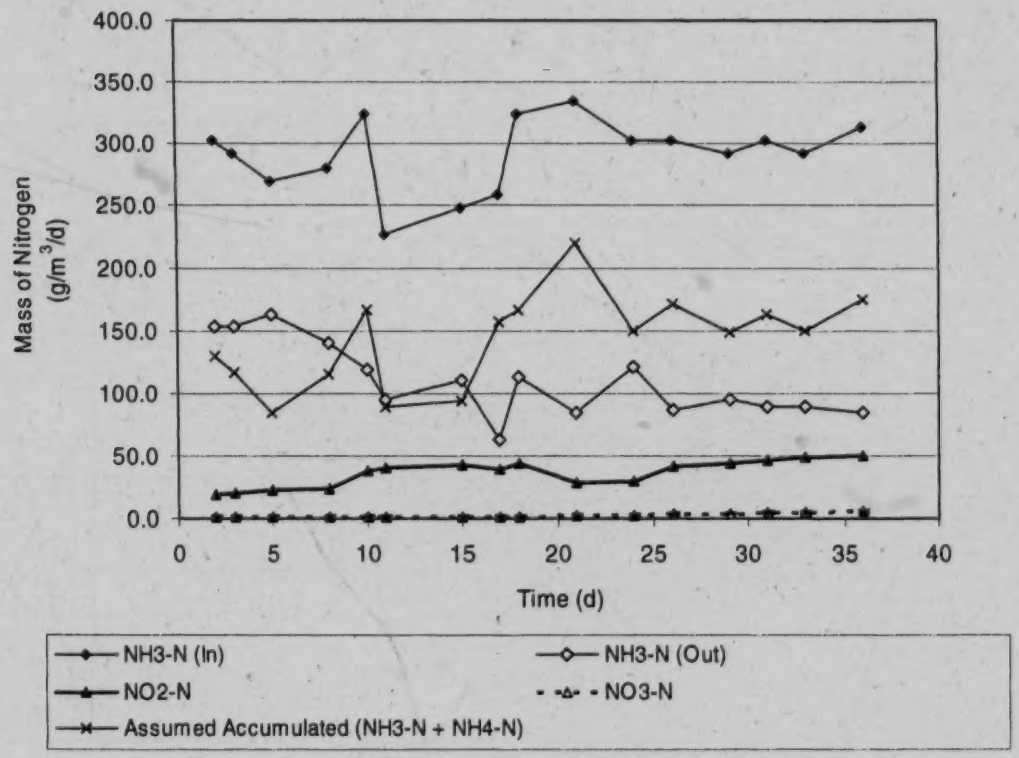


Figure 8.6 Overall mass balance of nitrogen in the biofilter (45 ppmv)

The factors of the mass balance equation in the biofilter 4 (90 ppmv) were 567.9±13.1, 325.8±19.8, 31.7±4.9, 0.4±0.1, and 211.6±21.5 $g/m^3/d$, respectively. The rate of nitrification was 13% of the EC, and no nitrate was produced in this biofilter (Figure 8.7). The accumulation rate of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ was 87% of the EC. Operating the biofilter with 10 s EBRT and availability of about 90 ppmv ammonia concentrations in the contaminated air can be assumed to provide the worst condition of toxicity due to the accumulation of nitrite and $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$.

There was no significant difference ($p>0.05$) between biofilter 2 (20 ppmv) and 3 (45 ppmv) for total nitrite and nitrate production, but there was a significant difference between these biofilters for nitrate production. The daily accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ in the biofilters (2, 20, 45, and 90 ppmv) was 3.4±2.9, 70.6±5.9, 143.4±10.5, and 211.6±21.5 $g/m^3/d$, respectively. However, the daily accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ linearly increased when the concentration of ammonia injection increased.

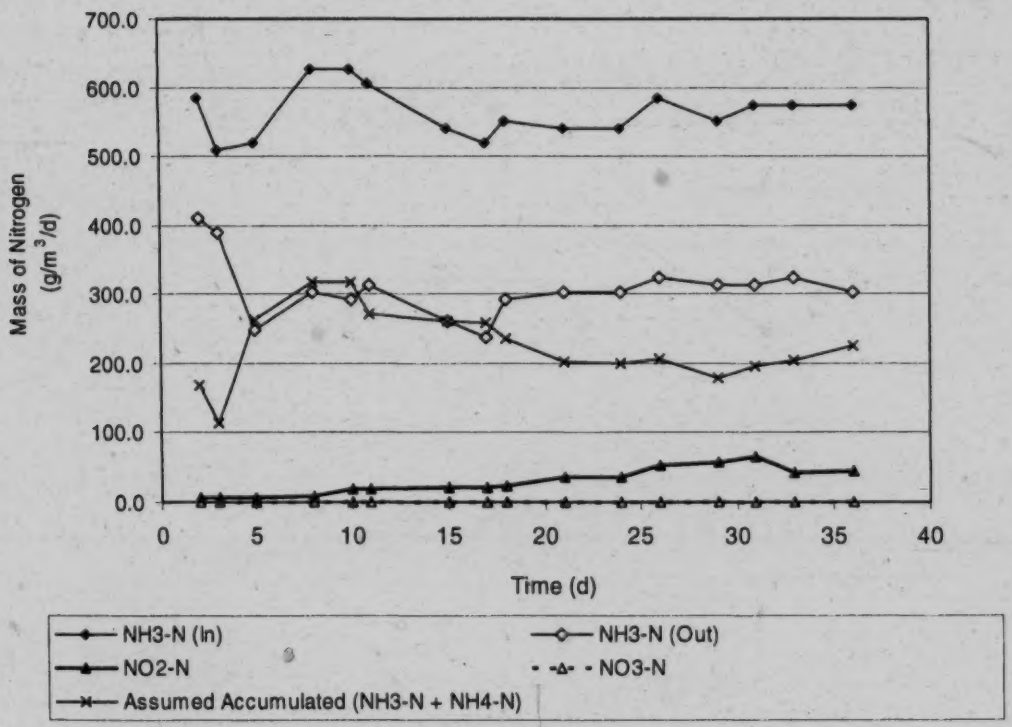


Figure 8.7 Overall mass balance of nitrogen in the biofilter (90 ppmv)

8.3.2 Summary of nitrogen mass balance

The results of the mass balance evaluation are based on the overall treatment means. Figure 8.8 and Table 8.1 show the overall quantity of the mass balance factors versus four levels of ammonia concentrations that the biofilters have received. The ammonia concentration increased from 1.9±0.4 to 21.5±0.7 ppmv, and the total nitrite and nitrate gradually increased. However, increasing the ammonia concentrations from about 20 to 90 ppmv did not significantly change ($p>0.05$) the daily production of nitrite nitrogen. With injections of 90 ppmv of ammonia, no nitrate was produced in the biofilters. The amount of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ was increased from 3.4±2.9 to 211.6±21.5 g/m^3/d when, the ammonia concentrations increased from about 2 to 90 ppmv (Table 8.1). The maximum capacity of the biofilters for nitrification was considered 42.1±3.9 g/m^3/d NH_3-N (Table 8.2). When more ammonia nitrogen enters the biofilter, it will accumulate

(absorption and adsorbtion) in the form of $\Sigma(NH_3\text{-}N + NH_4^+\text{-}N)$ unless leachate is removed. However, the rate of nitrification can change due to temperature, retention time, and type of biofilter media. Table 8.2 shows the overall results of biofiltration in the barn with 10s EBRT and the concentration of ammonia 2, 20, 45, and 90 ppmv. The elimination capacity (EC) for the above concentrations of ammonia were measured 11.64±2.6, 111.4±5.6, 183±10.9, and 242±21.8 $g/m^3/d$. Meanwhile, $\Sigma(NO_2^-\text{-}N + NO_3^-\text{-}N)$ was 8.6±1.5, 42.1±3.9, 40.8±4, and 31.9±5 $g/m^3/d$. From the overall elimination capacity, we can conclude that the concentration of ammonia at the inlet and outlet of the biofilter is not a good indicator for designing the biofilter. However, the total amount of nitrite and nitrate nitrogen appeared as a good indicator for evaluating the performance of the biofilter.

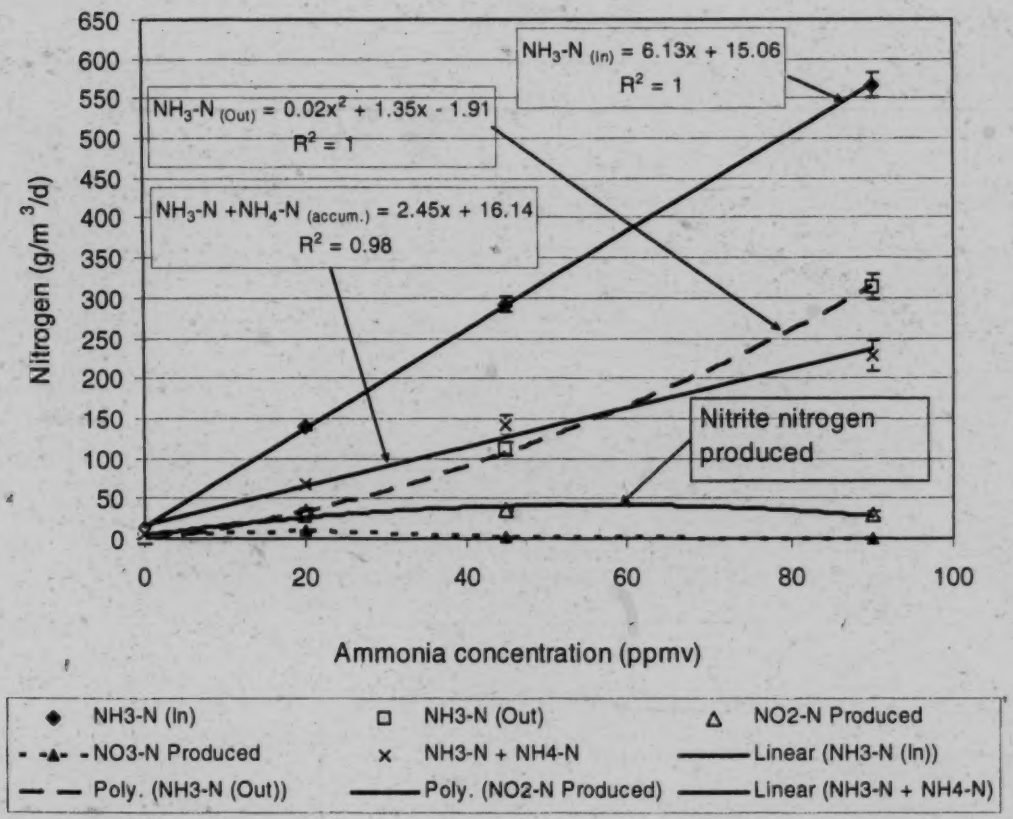


Figure 8.8 Overall nitrogen mass balances in the 2, 20, 45, and 90 ppmv ammonia biofilters

Table 8.1 Mean concentrations and amount of ammonia at the inlet and outlet of the biofilters, production of NO_2^--N and NO_3^--N, and the assumed accumulation of $\Sigma(NH_3\text{-}N + NH_4^+\text{-}N)$

Biofilter	NH_3 ppmv	NH_3-N (In) $g/m^3/d$	NH_3-N (Out) $g/m^3/d$	NO_2^--N $g/m^3/d$	NO_3^--N $g/m^3/d$	$\Sigma(NH_3\text{-}N + NH_4^+\text{-}N)$ $g/m^3/d$
1 (2 ppmv)	1.9±0.4	12.5±2.6	0.9±0.5	1.9±0.2	6.6±1.2	3.4±2.9
2 (20 ppmv)	21.5±0.7	139.6±4.6	28.2±3.4	30.4±4.4	11.7±1.5	70.6±5.9
3 (45 ppmv	46.8±1.5	302.9±9.6	119.9±10.5	37.9±3.7	2.9±0.4	143.4±10.5
4 (90 ppmv)	87.5±2.0	567.9±13.1	325.8±19.8	31.7±4.9	0.4±0.1	211.6±21.5

Table 8.2 Mean elimination capacity (EC), production of $\Sigma(NO_2^-\text{-}N + NO_3^-\text{-}N)$, removal of $\Sigma(NO_2^-\text{-}N + NO_3^-\text{-}N)$, and the amount of daily leachate from each biofilter

Biofilters	Elimination Capacity (EC) $g/m^3/d$	$\Sigma(NO_2^-\text{-}N + NO_3^-\text{-}N)$ produced $g/m^3/d$	$\Sigma(NO_2^-\text{-}N + NO_3^-\text{-}N)$ removed $g/m^3/d$	Leachate $L/m^3/d$
2 ppmv	11.64±2.6	8.6±1.5	3.2±0.4	14.0±0.5
20 ppmv	111.4±5.6	42.1±3.9	23.6±2.1	18.5±0.5
45 ppmv	183.0±10.9	40.8±4.0	22.3±3.0	20.4±0.7
90 ppmv	242.0±20.8	31.9±5.0	17.2±3.2	21.3±0.8

8.3.3 Removal Efficiency (RE) of the Biofilters

The removal efficiency is not a complete descriptor of biofilter performance because it varies with airflow, contaminant concentration, and biofilter size. It also only reflects the specific conditions in which it is measured. However, because the experiment was conducted under typical barn conditions, it can be useful for operating the biofilter in the barn. Figure 8.9 shows the overall RE of the biofilters. The removal efficiency of the biofilter (2 ppmv) ammonia concentration was 100%. The ranges of the RE of the other

biofilters with 20, 45, and 90 ppmv ammonia concentrations were 65 to 90, 55 to 70, and 40 to 45%, respectively. The removal efficiency of the biofilters with 20 and 45 ppmv ammonia concentrations were increased linearly through 36 days of operation. At the same time, the production of $\Sigma(NO_2^-N + NO_3^-N)$ increased linearly. There are two possibilities for underestimating the nitrification rate including: a) probably 14 days for acclimation of nitrifying bacteria is not enough, and b) accumulation of by-products, such as nitrite and nitrate provide more sources of nutrients for growth of the microorganisms.

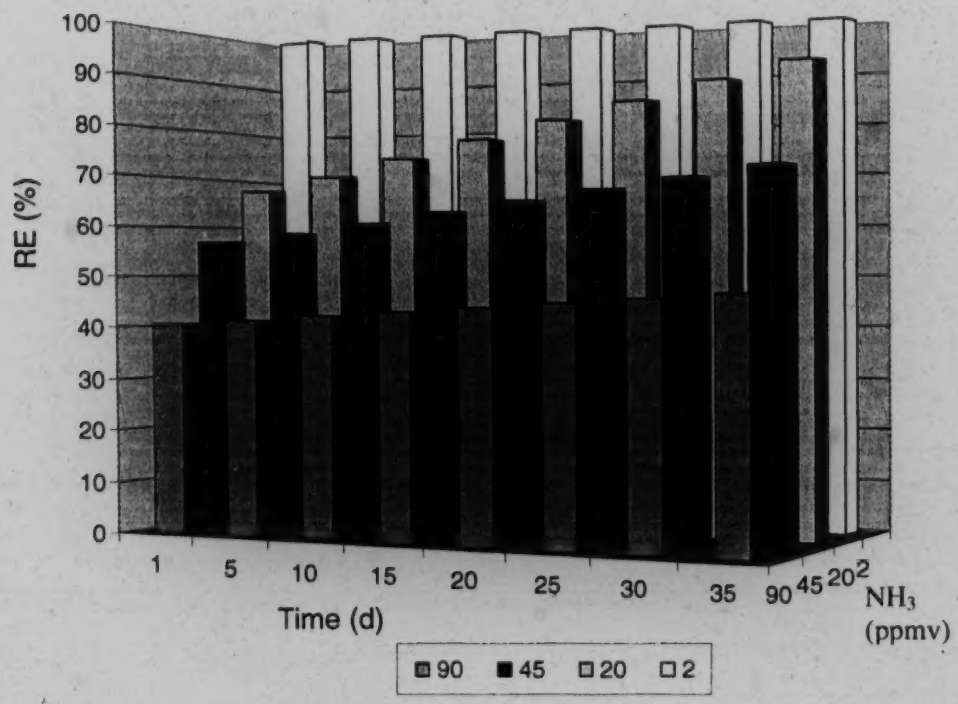


Figure 8.9 The overall ammonia removal efficiency (RE) of biofilters (2, 20, 45, and 90 ppmv ammonia)

8.4 Upgrading the Model

The designing and operation of the biofiltration system depends on many factors such as type and quantitative amount of odourants, media, moisture content of the media, empty bed retention time (EBRT), and temperature. However, in the design of biofiltration

system, it is essential to model the rate at which the toxic or odourous gases will be oxidized. Residence time and elimination capacity (EC) for biofilter reactors must be taken into account. Moreover, the pH value should be stabilized in the proper range. Designing proper water application and leachate collection should control the by-products. Figure 8.10 shows the strategy employed for providing quantitative data and development of a model for design and operation of the biofilters in livestock facilities. The literature review provides available information about biofiltration, production of odourants, and factors affecting biofilter performance.

We learned from the preliminary experiments that: a) water application is essential for designing and operating the biofilter and b) from technical and an economical criterion, selecting the right media is a fundamental requirement. However, the use of different materials and coarse compost with high absorbability of water and relatively low pressure drop showed better results c) the results of the preliminary experiments were extremely variable, partly because of compaction and channelling or of unstable and non-uniform moisture conditions in the filter media. Due to the lack of information about the by-product and amount of daily leachate, it was difficult to understand the reasons for the variation in the results.

Subsequently, a biofiltration system (a combination of bioscrubber and biofilter) was designed for achieving better control on the biofiltration system. From the successful operation of the biofiltration systems (a combination of bioscrubber and biofilter and a chemical scrubber and biofilter) in the treatment plant with relatively high NH_3 and H_2S, it is concluded that these gases have a major effect on the pH value. Moreover, it was found that when the concentrations of H_2S in the exhaust air of the treatment plant increases (more than 1 ppmv), the pH of the leachate gradually decreases to the acidic condition. The production of nitrite and nitrate can change the pH to an acidic condition, but the chemical tests during this period of time show that the accumulation of the sulfate causes a decrease in the pH values of the leachate of the biofilter. However, based on the above results for revising the model, the availability of the hydrogen sulfide concentrations in the contaminated air are limited in the model to less than 1 ppmv. Another biofiltration system, including four biofilters and one bioscrubber, was designed

for operation in the swine barn with a lower level of ammonia and hydrogen sulfide concentrations under normal operation of the barn (Chapters 6 and 7).

As mentioned earlier, this experiment was carried out with three replications and four treatments including no ammonia injection (control), and 20, 45, 90 ppmv NH_3 injections in to the inlet air. To evaluate the effect of ammonia on the biofilters' performance, many factors, such as temperature, pH, RH, empty bed residence time (EBRT), removal efficiency (RE), and elimination capacity (EC), were measured. To evaluate the effectiveness of the bioscrubber and the biofilters on odour concentrations, the olfactometry of the odour samples from the inlet and outlet of the bioscrubber and biofilters were conducted bi-weekly. To evaluate water application rates, factors that affect water application, such as temperature, relative humidity, amount of leachate from each biofilter, moisture content of the media, and electrical conductivities of the leachates, were monitored. In terms of mass balance evaluation, the other factors that were measured include airflow, concentrations of NH_3 and H_2S, and the volume of daily leachate of each biofilter. Moreover, chemical tests (sulfate, nitrite, and nitrate) were conducted to support the mass balance evaluation.

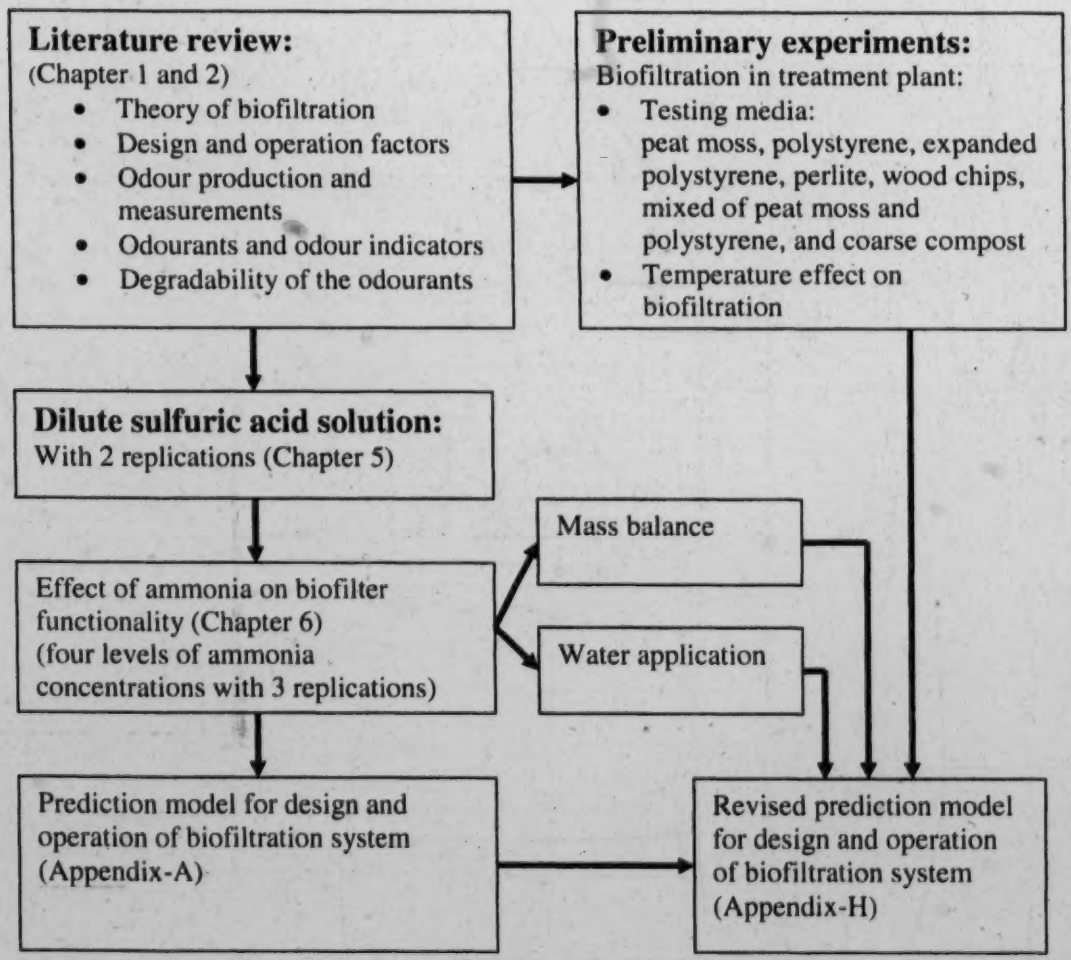

Literature review:
(Chapter 1 and 2)
Theory of biofiltration
Design and operation factors
Odour production and measurements
Odourants and odour indicators
Degradability of the odourants
Preliminary experiments:
Biofiltration in treatment plant:
Testing media:
peat moss, polystyrene, expanded polystyrene, perlite, wood chips, mixed of peat moss and polystyrene, and coarse compost
Temperature effect on biofiltration
Dilute sulfuric acid solution:
With 2 replications (Chapter 5)
Mass balance
Effect of ammonia on biofilter functionality (Chapter 6)
(four levels of ammonia concentrations with 3 replications)
Water application
Prediction model for design and operation of biofiltration system (Appendix-A)
Revised prediction model for design and operation of biofiltration system (Appendix-H)

Figure 8.10 The flowchart describes the strategy employed for upgrading the model in section 2.9

Finally, with the idea of combining the results of the experiments, the quantitative data from nitrogen mass balance, water application, and references, were used for revising the draft model (Appendix-A). The draft model was revised (Appendix-H) based on the following assumption:

- The H_2S concentration available in the contaminated air is lower than 1 ppmv. If the concentration of H_2S is higher than expected, the bioscrubber should be able to eliminate it to the certain level.

- The range of ammonia is between 0 to 20 ppmv. This range was chosen because when ammonia concentration reaches a level higher than 20 ppmv, nitrite becomes the primary by-product and the accumulation of the nitrite as a toxic material can reduce or stop the microbial activity.
- The empty bed retention time (EBRT = volume of the media/airflow) should be more than 20s because of the diffusion limitation. With 10s EBRT and 20 ppmv ammonia concentration, about 75% of ammonia is absorbed by the media. For increasing the EBRT, there are two options: a) increasing the volume of the media, or b) decreasing the airflow rate.
- The effect of temperature on the microbial activity has the same effect on the production of nitrite and nitrate nitrogen. The overall temperature of the experiment was 15°C. However, if the biofilter is operated at other temperatures, the effect of the temperature should be considered for design and operation of the biofilter.

The prediction model includes three stages (Figure 8.11): input (Table 2.10), processing the data based on references and outcome of the experiments with software making all the necessary formula or calculations provided from the results of the experiment or references, and the output (Table 2.11) clarifying the final prediction results.

The equations used in the model are:

The volume of the media (coarse compost materials) can be predicted based on the ability of the biofilter for nitrite and nitrate nitrogen production and the assumptions:

1) The entire amount of ammonia that enters the biofilter is eliminated to nitrite and nitrate.

2) Temperature affects microbial activity (equation 8-20) and has the same effect on the amount of nitrite and nitrate production assuming diffusion is not a limited factor at temperature higher than 15°C.

With the following equations resulting from the pilot scale biofilters, the volume of the media (V2) and EBRT can be predicted (line 1825 to 2070 of the model Appendix - H).

$$Y1 = 6.13(C1) + 15.06 \qquad (8\text{-}13)$$

$$Y2 = 0.024(C1)^2 + 1.35(C1) - 1.91 \quad (8\text{-}14)$$

$$Y3 = 0.013(C1)^2 + 1.482(C1) - 1.41 \quad (8\text{-}15)$$

$$Y4 = 0.254(C1) + 4.17 \quad (8\text{-}16)$$

$$Y5 = Y1 - Y2 - Y3 - Y4 \quad (8\text{-}17)$$

$$V2 = \frac{cgit}{(Y3+Y4)a} \quad (8\text{-}18)$$

$$EBRT2 = \frac{V2\times 1000}{qs} \quad (8\text{-}19)$$

$a = e^{0.098(T-15)}$ (Metcalf and Eddy, 1991). (8-20)

Where under experimental conditions and specific ammonia concentration (C1 ppmv) the predicted values are:

Y1 = Ammonia nitrogen that biofilter can take in ($g/m^3/d$),

Y2 = Ammonia nitrogen that can go out from the biofilter by air ($g/m^3/d$),

Y3 = Nitrite nitrogen that can be produced in the biofilters ($g/m^3/d$),

Y4 = Nitrate nitrogen that can be produced in the biofilters ($g/m^3/d$),

Y5 = Total ammonia and ammonium nitrogen that can be accumulated or removed from the biofilter ($g/m^3/d$),

cgit = The amount of ammonia nitrogen entering the biofilter(cgit) can be estimated by equations 8-4 to 8-7,

C1 = the concentration of ammonia available in the contaminated air (ppmv),

T = (T1+T2)/2 where: T1 and T2 are the temperatures of the contaminated air at the inlet and outlet of a biofilter, respectively,

a = Effect of temperature on microbial activity,

e= 2.718,

qs = airflow (L/s), and

V2 = minimum volume of the compost media needed (m^3).

The equations to predict the amount of water needed for the humidifier (W) are included in the model line 2110 to 2380 (Appendix-H). However, the input data are: airflow (L/s) = qs, temperature (°C) = t1 and t2, and relative humidity (%) = rh1 and rh2.

Prediction of amount of water needed for chemical control:

Line 2095 to 2110 of the revised model (Appendix H) shows the following equations.

$$Wa = V2 \times (0.258 \times C1 + 12.884)/1000 \quad (8\text{-}21)$$

$$Wa1 = V2 \times (1.394 \times C1 + 15.311)/1000 \quad (8\text{-}22)$$

Where:

Wa = minimum range of water needed for flushing the chemicals before 36 days of operation (m^3/m^3 medium/d),

Wa1 = maximum range of water needed for flushing the chemicals after 36 days of operations (m^3/m^3 medium/d), and

C1 = concentration of ammonia at the inlet of the biofilter (ppmv).

Other operational factors under experimental conditions, such as EC, RE, and pH can be predicted by equations from line 1415 to 1520 of the model.

$$RE = 0.0047(C1)^2 - 1.04(C1) + 99.24 \quad \text{(line 1450 model)} \quad (8\text{-}23)$$

$$C2 = (100 - RE) \times C1/100 \quad \text{(line1455 model)} \quad (8\text{-}24)$$

$$cgi = (q1 \times 17 \times 453 \times C1)/(28.3 \times 378.87 \times 1000{,}000) \quad \text{(line1460 model)} \quad (8\text{-}25)$$

$$cgo = (q1 \times 17 \times 453 \times C2)/(28.3 \times 378.87 \times 1000{,}000) \quad \text{(line1460 model)} \quad (8\text{-}26)$$

$$EC = (cgi - cgo)/0.15 \quad \text{(line 1480 model)} \quad (8\text{-}27)$$

Where:

q1 = 20 L/s

C2 = prediction of the concentration of ammonia at the outlet of the pilot scale biofilter (ppmv),

cgi = estimation of mass of the ammonia that the biofilter can receive under experimental conditions (g/d),

cgo = estimation of the mass of ammonia that can exit the biofilter under experimental conditions (g/d), and

EC = the mass of ammonia that can be absorbed by the biofilter ($g/m^3/d$).

Prediction of nitrite and nitrate concentrations in the biofilters' leachate under experimental conditions on a certain day (d1) is done based on the ammonia concentration (C1) with a range of 2 to 90 ppmv at the inlet. By using the following equations, we can estimate the concentration of nitrite in the leachate:

$$N1 = 0.126 \times (d1)^2 - 0.155 \times d1 + 156 \quad (8\text{-}28)$$

$$N2 = -6.71 \times (d1)^2 + 355.94 \times d1 + 384.56 \quad (8\text{-}29)$$

$$N3 = 141.6 \times d1 + 289.02 \quad (8\text{-}30)$$

$$N4 = 4.87 \times (d1)^2 - 26.81 \times d1 + 499.93 \quad (8\text{-}31)$$

Where:

d1 = days of operation after day 14 (range: 1 to 36),

N1, N2, N3 and N4 = concentration of the nitrite in the leachate of biofilters at day d1 (ppm) operated with C3=2, C4=21, C5=45, and C6=87 ppmv ammonia concentrations.

$$ma = (N2 - N1) / (C4-C3) \quad (8\text{-}32)$$

$$Ya = N1 + ma \times (C1-C3) \quad (8\text{-}33)$$

$$mb = (N3-N2) / (C5-C4) \quad (8\text{-}34)$$

$$Yb = N2 + mb(C1-C4) \quad (8\text{-}35)$$

$$mc = (N4-N3)/(C6-C5) \quad (8\text{-}36)$$

$$Yc = N3 + mc \times (C1-C5) \quad (8\text{-}37)$$

Where:

ma, mb, and mc = slopes of the lines of nitrite concentration between two levels of ammonia concentrations at the inlet, and

Ya, Yb, and Yc = the concentration of nitrite in the leachate of a bifilter operated with ammonia concentration (C1) at the inlet.

The estimation of nitrate concentration of the leachate is similar to the above equations for nitrite. However, all the necessary equations for predicting the nitrite and nitrate concentrations in the leachate are included in the revised model (line 2480 to 3190 Appendix - H). By entering the ammonia concentration (C1) and day of operation (d1) in the model, the concentrations of nitrite and nitrate will be predicted. The important capital and operating costs of a biofilter can also be predicted from lines 3190 to 3470 of the revised model.

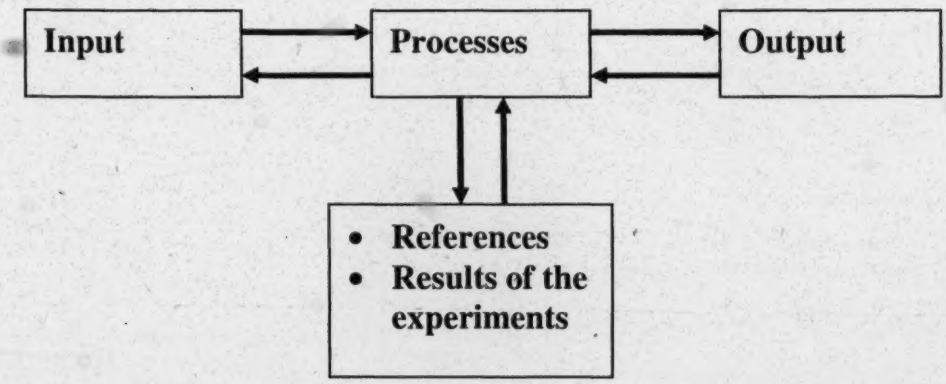


Figure 8.11 The flow chart of the predicting model for designing and operating a biofilter in animal facilities

8.4.1 Testing the Model for Water Application

Water for humidifying the air:

The model was tested under different ammonia concentrations, temperature, airflow, relative humidity, etc. Figure 8.12 shows the prediction of the amount of water that is needed for humidifying the contaminated air under different conditions of operation. The prediction model can predict the amount of water needed for any size and operation condition. As Figure 8.12 shows, there is high variation between different conditions of operation. For having more accuracy for prediction, it is recommended that input data, including airflow, temperature and RH of the inlet and outlet be measured with ±5% accuracy.

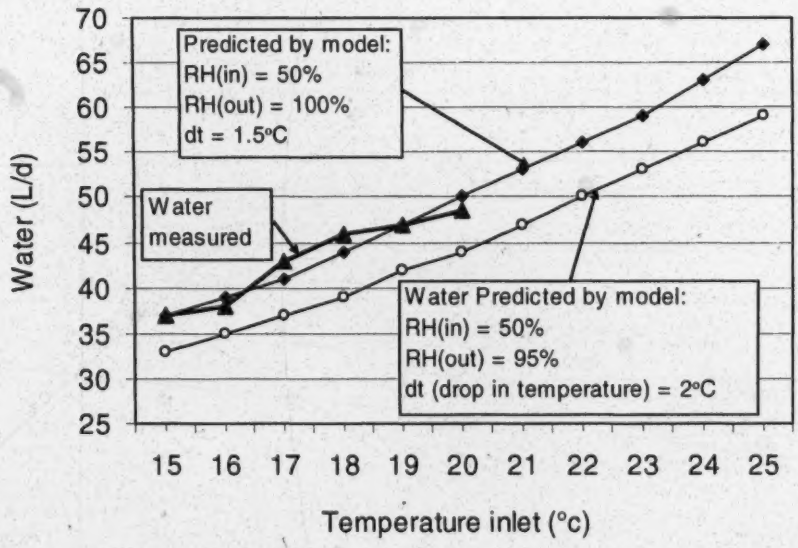


Figure 8.12 Predicting the amount of water for a biofilter that will be operated with temperature 15 to 25°C and airflow 80 L/s

Predicting the amount of water for removing the by-products:

The measurement of the nitrite and nitrate along with monitoring the volume of the biofilters' leachate helps to predict the optimum amount of leachate needed for controlling the by-products in the biofilters. In Chapter 7, the methods of controlling the by-products were explained. Figure 8.13 shows the overall ranges of water application for controlling the nitrite and nitrate. If the ammonia concentrations in the contaminated air

vary between 2 to 20 ppmv and the biofilter operates under experimental conditions, the minimum amount of water prediction is 13 to 18 L/m^3/d. However, the maximum amount of water for controlling the by-products is 18 to 45 L/m^3/d.

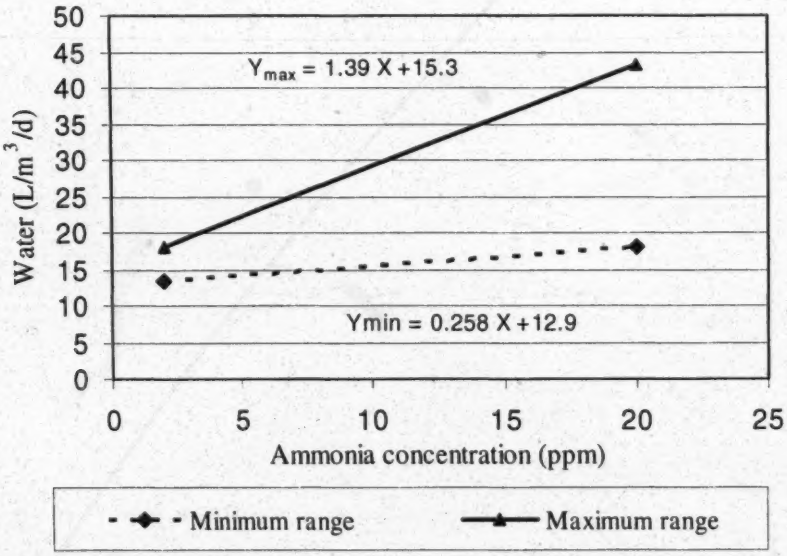


Figure 8.13 The amount of water is required for controlling the by-products can be estimated from this graph based on the ammonia concentrations in the contaminated air

With the measurement of electrical conductivity or total dissolved solids (TDS) of the biofilter leachate, we can adjust the optimum amount of water needed for controlling the by-products.

Prediction of minimum volume of the media:

The results of the mass balance show that the compost biofilters (operated with more than 20 ppmv ammonia concentration) produced 42±3.9 g/m^3/d total nitrite and nitrate nitrogen with the overall elimination capacity of 111.4±5.6 g/m^3/d and a removal efficiency of 75%. The nitrification processes in this biofilter seems to be limited by microbial reaction because about one third of the elimination capacity transformed to nitrite and nitrate. At a temperature greater than 20°C, it may be operated with a limitation of loading or diffusion. The volume of the compost media will be predicted based on quantity amount of ammonia nitrogen available per day and overall capacity of

production of $\sum(NO_2^-N + NO_3^-N)$ in the experiment with the effect of temperature. If the needed EBRT calculated by the model is lower than 20s and the temperature is higher than 18°C the volume of the media will automatically be based on 20s retention time. Figure 8 .14 shows output of the model (the prediction of the minimum volume of the media 90 to 40 m^3 and relevant EBRT 45 to20s) based on input parameters: airflow (qs) = 2,000L/s, ammonia concentration = 20 ppmv, inlet temperature at the inlet (T1) = 10 to 25°C, outlet temperature (T2) = 10 to 25°C, relative humidity at the inlet (RH_1) = 50%, relative humidity at the outlet (RH_2) = 95%, and empty bed retention time (EBRT)>=20s. However, the minimum volume of the media decreased from 90 to 40 m^3 when the temperature increased from 10 to 18°C.

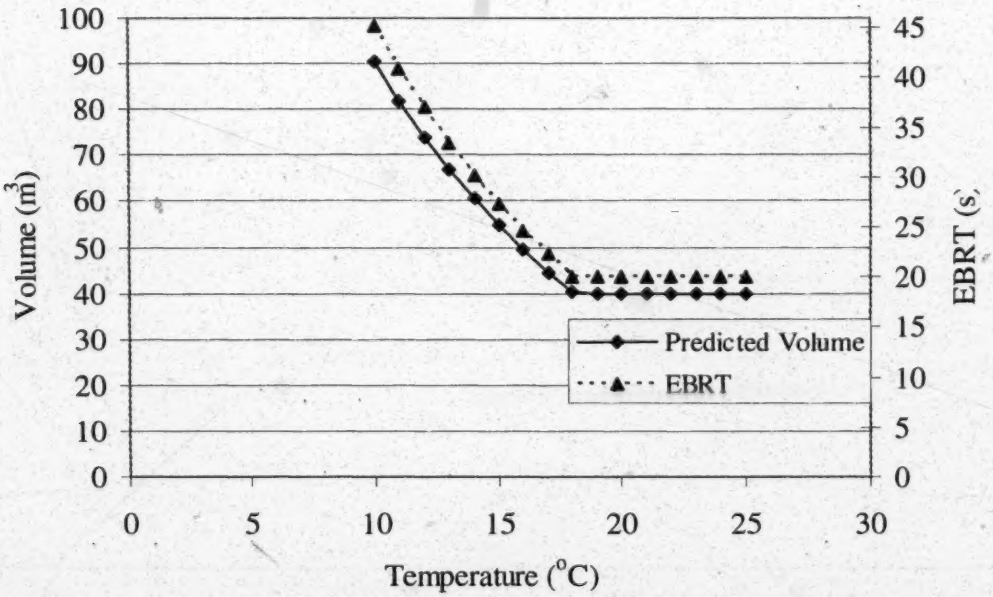


Figure 8.14 The prediction of the minimum volume of media and for treating 2,000 L/s of contaminated air at 10 to 25°C with 20 ppmv ammonia concentrations and >=20s EBRT

Figure 8.15 shows the output of the model (the prediction of the minimum volume of the media 40 to 55 m^3 and relevant EBRT 20 to27s) based on input parameters: airflow (qs) = 2,000L/s, ammonia concentration = 2 to 20 ppmv, inlet temperature at the inlet (T1) = 15°C, outlet temperature (T2) = 15°C, relative humidity at the inlet (RH_1) = 50%, relative

humidity at the outlet (RH_2) = 95%, and empty bed retention time (EBRT)>=20 s. The range of the predicted volume in this figure is lower than what was shown in Figure 8.14 because temperature is constant and performance of the biofilter will be limited by diffusion or load.

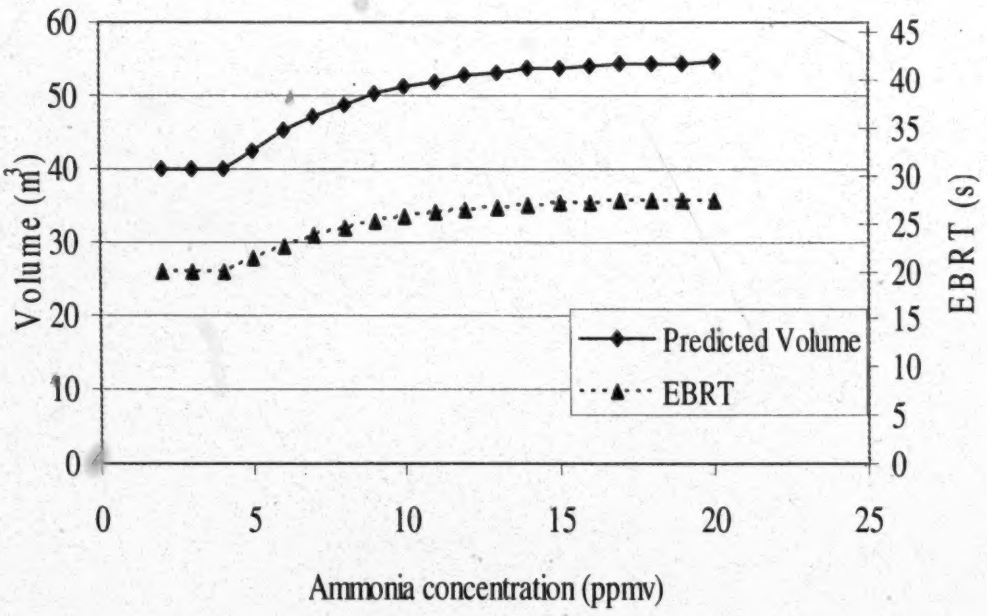


Figure 8.15 The prediction of the minimum volume of media and for treating 2000 L/s contaminated air at 15°C with 2 to 20 ppmv ammonia concentrations and EBRT>=20s

Some operational factors, such as EC, RE, and pH can be predicted by the prediction model under experiment conditions. The prediction of these factors is useful for biofilter operator. As an example, Figure 8.16 shows the prediction of the EC of a biofilter for ammonia when it is operated in the barn (ammonia concentrations = 2 to 20 ppmv, and average temperature = 15 °C).

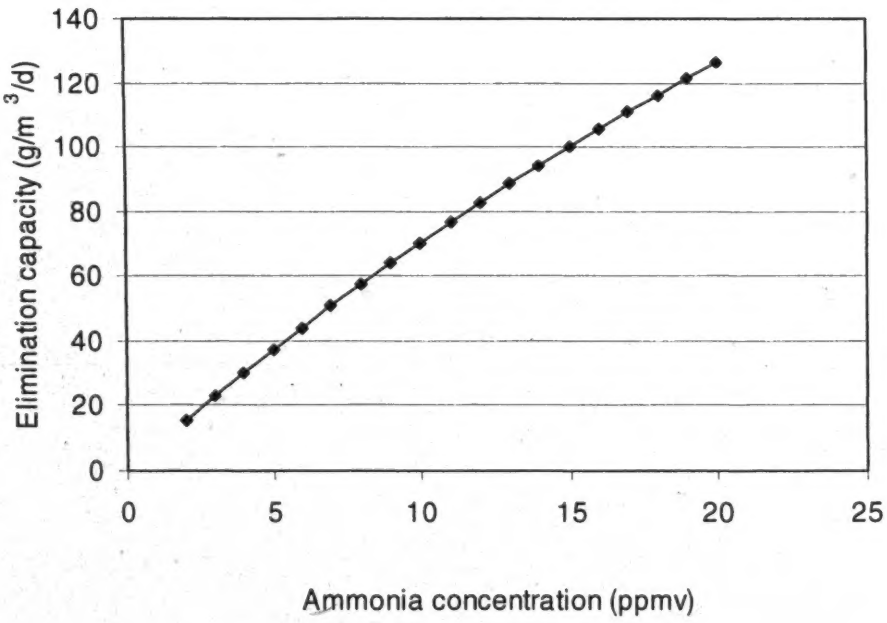


Figure 8.16 The prediction of the elimination capacity of a biofilter for ammonia when operated with 2 to 20 ppmv ammonia concentrations and experiment conditions

8.5 Conclusions

1. The overall elimination capacity (EC) of the biofilters were operated with 2, 20, 45, and 90 ppmv ammonia concentrations were: 11.6±2.6, 111±5.6, 183±10.9 and 242±21.8 $g/m^3/d$ ammonia nitrogen. Meanwhile, the $\sum(NO_2^-N + NO_3^-N)$ were: 8.6±1.5, 42±3.9, 41±4 and 32±5 $g/m^3/d$. However, the rates of transformation of ammonia nitrogen to total nitrite and nitrate nitrogen for the above biofilters were: 73, 38, 22, and 13% of the EC of each biofilter.

2. The productions of the NO_2-N in the above biofilters were: 1.9±0.2, 30.4±4.4, 37.9±3.7, and 31.7±4.9 $g/m^3/d$, respectively. However, the results show that nitrite may accumulated in the biofilters if operated at more than 20 ppmv ammonia concentrations and 10s EBRT if the amount of leachate is lower than 18 $L/m^3/d$.

3. The results of the mass balance showed that the compost biofilters (operated with more than 20 ppmv ammonia concentration) produced 42±3.9 $g/m^3/d$ total nitrite and nitrate

nitrogen with the overall elimination capacity of 111.4±5.6 g/m^3/d and removal efficiency of 75%.

4. The daily accumulations of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ in the biofilters were operated with the above ammonia concentration were: 3.4±2.9, 71±5.9, 143±10.5, and 212±21.5 g/m^3/d. However, daily accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ linearly increased when the concentration of ammonia injection increased.

5. The removal efficiency of the biofilter that received about 2 ppmv from the barn was 100%. The ranges of the RE of the other biofilters with 20, 45, and 90 ppmv ammonia concentrations were 65 to 90, 55 to 70, and 40 to 45%.

6. The overall daily amount of the leachate of the biofilters operated with 2, 20, 45, and 90 ppmv ammonia concentrations were: 14.0±0.5, 18.5±0.5, 20.4±0.7, and 21.3±0.8 L/m^3/d, respectively. These amounts of leachate removed about 50% of the daily production of $\sum(NO_2^-\text{-}N + NO_3^-\text{-}N)$ from the biofilters. However, with using the upgraded model, the optimum water application can be predicted.

7. Temperature is the important factor that can affect the volume of the media required. For example, for 2,000 L/s contaminated airflow with 20 ppmv ammonia concentrations at a temperature of 10 to 25°C, the minimum volume of the compost media predicted is 90 to 40 m^3. However, the EBRT is considered for temperatures above 45 to 20s.

8. The ammonia concentration is another factor that can affect the prediction of the volume of the media is required. For an example, the volume of the media is predicted 40 to 55 m^3 with the relevant EBRT 20 to 27s under the conditions: 2000 L/s airflow = 2000 L/s, the concentrations of ammonia = 2 to 20 ppmv, and at a temperature = 15°C.

9. The model is able to predict the volume, nitrite, nitrate, and EBRT for any conditions of temperature and ammonia concentrations (0 to 20 ppmv) and contaminated airflow.

8.6 References

Devinny, J. S., M.A. Deshusses and T.S Webster, 1999. Biofilteration for Air Pollution Control. Lewis Publishers, New York, USA.

Gibbons, M.J. and Loehr, R.C., 1998. Effect of media nitrogen concentraion on biofilter performance, J. Air Waste Manage. Assoc., 48(3), 475.

Metcalf and Eddy, Inc. 1991. Wastewater engineering: Treatment, disposal, and reuse (3rd edition). McGraw-Hill, Inc. New York. NY.

Metcalf & Eddy, Inc. 1993. Wastewater engineering: treatment, disposal, and reuse (4rd edition). McGraw-Hill, Inc. New York. NY.

Reynolds, T.D. and Richards, P.A, 1996. Unit operations and processes in environmental engineering (second edition). PWS publishing company, Boston. Ma.

Schnoor, J.L. 1996. Environmental modeling fate and transport of pollutants in water, air, and soil. A Wiley-Interscience publication (John Wiley and Sons, !nc. New York. NY.

Sun, Y., C.J. Clanton, K.A. Janni, and G.L. Malzer, 2000. Sulfur and Nitrogen Balances in Biofilters For Odour Gas Emission Control. ASAE Paper Vol. 43(6): 1861-1875.

9. OVERALL SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Overall Summary and Implications

Biofilters operate under two types of conditions: a) low load, a steady state water phase, and a microbial ecosystem where nutrient content can be maintained and continually recycled; or b) high load operation with growing biomass and possible issues, such as by-product accumulation, clogging, and lack of nutrients, in the biofilter media. In confinement livestock facilities, such as pig barns, there is the potential of high concentration of ammonia, hydrogen sulfide, and other odourous contaminants. Therefore, to use the biofiltration technology in these facilities efficiently, we must focus on type b (high load) operation. However, our experience with preliminary experiments with single stage biofiltration using different materials, such as peat moss, polystyrene, wood chips, mixes of them (with and without nutrients), shows that water application for leachate flow is essential to the biofiltration process. The results of the preliminary experiment were extremely variable, partly because of compaction and channelling or of unstable and non-uniform moisture conditions in the filter media. Due to the lack of information about the concentration of by-products and amount of daily leachate, it was difficult to understand the reasons for the variation in the results.

Subsequently, a combination of bioscrubber and biofilter was designed for achieving better control on the biofiltration system. Two sets of this system were constructed and were operated to treat the exhaust air from a treatment plant. The coarse compost material was used in the biofilters in three layers for preventing possible compaction. The expanded polystyrene and perlite was used in the bioscrubbers. Dilute sulfuric acid was used in one of the bioscrubbers. Parameters, such as temperature, relative humidity, NH_3, H_2S, etc., were monitored to evaluate the performance of the system. Moreover, the volume of the leachate was measured daily and chemical tests on the leachate were conducted biweekly. The overall outcomes of this experiment indicate that: the concentrations of hydrogen sulfide and ammonia are important factors that affect the pH and performance of the biofilters, and that a combination of bioscrubber and biofilter reduces the odour concentration under stable condition.

From the successful operation of the combination of bioscrubber and biofilter in the

treatment plant, (Experiment 1) another biofiltration system, including four biofilters and one bioscrubber, was designed for operation in the swine barn with a lower level of ammonia and hydrogen sulfide concentrations under normal operation of the farm. The main objective of this experiment (Experiment 2) was considering nitrogen mass balance and providing data for development of the predicting model for the design and operation of the biofilters in the animal facilities.

This experiment was carried out with four treatments, including no ammonia (control), and 20, 45, 90 ppmv ammonia injected to the inlet air. The results of the measurement of the temperature, relative humidity (RH), and airflow were used to predict that water is needed for humidifying the air for any size and condition of a biofilter. Finally, the predictive model was revised based on the results of this experiment in order to design and operate a biofilter in animal facilities. The model is valid for contaminated air with low concentration of H_2S (<1 ppm) and lower than 20 ppm ammonia, such as the contaminated air that will be available in the swine barn. The minimum volume of media and EBRT of the biofilter were predicted by using two methods including: a) based on elimination capacity of the pilot scale biofilter with the effect of temperature, and b) based on the mean daily production of the $\sum(NO_2^-N + NO_3^-N)$ with the effect of the temperature. Elimination capacity is not a reliable variable for estimating the minimum volume of the biofilter. Prediction of the media volume based on nitrite and nitrate production capacity with the effect of temperature is more reasonable. The EBRT is estimated to be more than 20 s. There are three steps for using the prediction model including input data such as airflow (L/s), temperature of the contaminated air at the inlet and outlet (°C), ammonia concentration of the contaminated air (ppmv), hydrogen sulfide concentrations at the inlet and outlet (ppmv), relative humidity of the air at the inlet and outlet of the biofilter, etc. The input data will be processed based on results of the experiment or using data from the literature. A two pages output provides the predicted values that are needed for biofilter design and operation.

9.2 Overall Conclusions

Preliminary experiment: This experiment featuring single-stage biofiltration (biofilter without humidifier) indicated that water application is essential to the biofiltration process. The results of the experiments were extremely variable, partly because of compaction and channelling or of unstable and non-uniform moisture conditions in the filter media. Due to the lack of information about the by-product and amount of daily leachate, it was difficult to understand the reasons for the variation in the results.

Experiment1: A combination of bioscrubber and biofilter treating the treatment plant air generated the following conclusions:

- The mixture of coarse compost and wood particles has better performance in terms of odour reduction and elimination capacity than other media.
- The measurement of nitrite, nitrate, and sulfate in the leachate of the biofilters indicates that the concentrations of NH_3 and H_2S in the contaminated air are the main factors that cause the variation of the pH of the biofilters.
- This biofiltration system has better performance of odour removal and low variations of pH, pressure drop, and moisture content of the media.
- Bioscrubbers with 4s retention times provide 95 to 100% relative humidity for the contaminated air.
- Ammonia and hydrogen sulfide reduced with the range of 94 to 100% and 80 to 85%, respectively.
- The ammonia elimination capacity of the bioscrubbers with and without acid was measured to be 264±13 and 194±13 $g/m^3/d$, respectively. The elimination capacity of the biofilters (after the bioscrubber) with acid and without acid was 25±4.5 and 55±5.3 $g/m^3/d$, respectively.
- Bioscrubbers with 4s EBRT reduced the odour concentration from 676±300 OU/m^3 by up to 58%. Bioscrubbers in combination with biofilters were associated with overall odour reductions of 63%. Changes in hedonic tone ranged from 5 to 12%.
- Nitrite was produced predominantly in bioscrubber without acid with the range of 1.500 to 4.800 ppm, and nitrate production was negligible.
- The nitrification processes were conducted in the biofilters with production of nitrite

and nitrate.

Experiments 2: This experiment featured a combination of one bioscrubber and four biofilters in the barn generated the following conclusions:

- Under normal operation of the swine barn, the concentrations of hydrogen sulphide are not high enough to affect the biofiltration system. Concentrations of ammonia, however, may be a limiting factor for the system. Ammonia concentrations of 2, 20, 45 and 90 ppmv differently affect the elimination capacity (EC), removal efficiency (RE), and pH of the biofilters ($p<0.05$).
- Combining the biofilter and bioscrubber is associated with more stable temperatures throughout the biofilter media, which is important for effective microbial activity.
- The mass balance results showed that by increasing the ammonia concentration, the elimination capacity (EC) and daily assumed accumulation of total ammonia and ammonium of the biofilters linearly increased. At the same time, the rate of nitrification was constant. In order to create a balance between the EC and nitrification process rate, the biofilter needs to operate with lower than 20 ppmv ammonia or to increase the EBRT.
- The biofilter with 20 ppmv ammonia produced the maximum amount of nitrate, and the biofilter with 90 ppmv ammonia concentration produced no nitrate.
- When the concentration of ammonia increased from 2 to 90 ppmv, RE of biofilters for ammonia decreased from 100 to 44±5.9 %.
- The biofiltration system (a combination of bioscrubber and biofilter) with no ammonia injection and 11s EBRT reduced the odour concentrations from 209 to 58 OU_E/m^3 (72%) and hedonic tone 22%.
- Water application is the most important factor in biofilter operation. It is important not only for providing enough moisture content but also for controlling the concentration of by-products, such as nitrite and nitrate, and toxicity in the media.
- The temperature, relative humidity of the contaminated air at the inlet and outlet of the biofiltration system, and the airflow are the main factors for predicting the amount of water needed for humidifying the contaminated air. Now, with the predicting model we are able to predict the amount of water needed for air humidification or controlling the by-product concentration.

- For the biofilters that operated with 20, 45, and 90 ppmv ammonia after 32 to 36 days of operation, the total concentrations of nitrite and nitrate reached 3,000 ppm. The range of water needed for washing out the by-products is 18±0.45 to 44 $L/m^3/d$.
- The pressure drop varied between 24.5 and 69 Pa through the bioscrubber and 59 to 88 Pa through the biofilters. EBRTs were estimated to be 4 and 8s for the bioscrubber and biofilters, respectively.
- The results indicate that the more noticeable air temperature alterations happened when air passed through the scrubber; temperature changes brought about by the biofilters afterwards were negligible. There were no significant differences ($P>0.05$) between the temperatures of the biofilters. The overall average temperature of the biofilters was 15.0±0.3°C.
- The overall mean RH of the air at the scrubber inlet and outlet was 50 and 100%, respectively. Meanwhile, the overall average RH of the air at the outlet of the biofilters was 92%. Statistically, there were no significant differences ($P<0.05$) between the RHs of the air at the outlets of the biofilters.
- The overall averages of the pH values were 7.49±0.04, 8.00±0.04, 8.3±0.04, and 8.6±0.04 for the biofilters that received 2, 20, 45, and 90 ppmv ammonia concentrations.
- Since there was a low H_2S concentration in the air (0.3±0.2 ppmv), the sulphate concentrations of the biofilters' leachate were constant.
- The nitrite and nitrate measurement results show that there were significant differences ($p<0.05$) between nitrite production in biofilter (2 ppmv) and the other biofilters with 20, 45, and 90 ppmv ammonia injection. There were no significant differences ($p>0.05$) in nitrite nitrogen production from biofilters with 20, 45, and 90 ppmv ammonia injection. However, there was a significant difference in nitrate production between biofilters with 20 ppmv and biofilters with 45, and 90 ppmv ammonia injections.
- The elimination capacity (EC) is a normalized factor. The mean values of the EC for the biofilters were 11.6±2.6, 111.4±5.6, 183±10.9, and 242±20.8 $g/m^3/d$ for the biofilters with 2, 20, 45, and 90 ppmv ammonia concentrations, respectively.
- The mean daily production of NO_2^--N in the biofilters was 1.9±0.2, 30.4±4.4,

37.9±3.7, and 31.7±4.9 g/m^3/d for the biofilters with 2, 20, 45, and 90 ppmv ammonia concentrations.

- The mean daily production of NO_3^--N in the biofilters was 6.6±1.2, 11.7±1.5, 2.9±0.4, and 0.4±0.1 g/m^3/d for the biofilters with 2, 20, 45, and 90 ppmv ammonia concentrations.
- The mean daily accumulation of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$ in the biofilters was 3.4±2.9, 70.6±5.9, 143.4±10.5, and 211.6±21.5 g/m^3/d for the biofilters with 2, 20, 45, and 90 ppmv ammonia.
- The upgraded model predicted EC, RE, pH, NO_2^--N, NO_3^--N, volume of the media, and water needed for a biofilter satisfactory.

9.3 Recommendations

- The electrical conductivity can be used to monitor performance of the biofilters on a continuous basis.
- More research is needed to understand why the nitrification processes normally will not be completed by nitrate production in the bioscrubber.
- Since the nitrification rates of the biofilters linearly increased through this experiment, a longer study of biofilter performance in animal facilities is recommended.
- The result of this study indicate that the overall elimination capacity (EC) of the biofilter with 20 ppmv ammonia and 10s EBRT was 111±5.6 g/m^3/d. At the same time, the maximum production of total nitrite and nitrate nitrogen was 42±3 g/m^3/d. However, 38% of the ammonia nitrogen was eliminated to nitrite and nitrate, and the rest (62%) assumed accumulated in the form of $\sum(NH_3\text{-}N + NH_4^+\text{-}N)$. Increasing the EBRT to greater than 10s is highly recommended.
- The ammonia elimination capacity of a biofilter is not a good factor for designing a biofilter because ammonia accumulates in the water as ammonia and ammonium. However, the rate of production of total nitrite and nitrate quantitatively seems to be a good factor.
- The bioscrubbers with 4s EBRT removed more than 50% of the odour concentration in the treatment plant and inside the barn, making it an economical option for odour

control in animal facilities.

- Two-step biofiltration systems with proper EBRT seem to be suitable for odour reduction in animal facilities. Additionally, this system has high potential for treating the warm and moist air from composting facilities, in that it stabilizes ammonia to form nitrate.
- Biofiltration systems can be used effectively in the area of aquaculture (intensive fish farming) for improving the water quality and stabilizing the dissolved ammonia.
- For biofilters to become practical in animal facilities – notably pig barns – the pressure drop would need to be very low to minimize power and equipment requirements, and choosing the right media would be crucial.
- Adequate amounts of water for humidifying the air and maintaining non-toxic concentrations of by-products are central to effective operation of biofiltration technology in animal facilities.

Appendix A: Draft Predicting Model

```
10 ' Predicting model for design and performance of
biofilter based on inlet ammonia concentration
20 CLS : PRINT "Predicting model for design and performance
of biofilter"
25 CLOSE
30 PRINT
40 PRINT
50 KEY OFF: WIDTH 80, 50: COLOR 7, 0: TRUE = 1: FALSE = 0
60 CLS : GOSUB 3530: PRINT : PRINT   'Header and
introduction
70 PRINT TAB(10); "           This biofiltration model
predicts design and "
80 PRINT TAB(10); "operating parameters including: removal
efficiency (RE),"
90 PRINT TAB(10); "elimination capacity (EC), empty bed
retention time "
100 PRINT TAB(10); "(EBRT), volume of media, pH, by-products
such as nitrite"
110 PRINT TAB(10); "and nitrate, amount of water needed for
evaporation or  "
120 PRINT TAB(10); "increasing the relative humidity (RH) of
the polluted air,"
130 PRINT TAB(10); "and amount of water for controlling pH
and toxicity of  "
140 PRINT TAB(10); "the by-products.The prediction of the
above parameters  "
150 PRINT TAB(10); "have conducted based on nitrogen mass
balance, availability"
160 PRINT TAB(10); "of the contaminated airflow, temperature
(inlet and"
165 PRINT TAB(10); "outlet), ammonia and hydrogen sulfide
concentrations, RH at"
170 PRINT TAB(10); "the inlet and outlet of biofilter, days
of operation"
180 PRINT TAB(10); "(14 days after starting the opertation).
Finally, except"
190 PRINT TAB(10); "overhead capital and operation costs
including power, water"
200 PRINT TAB(10); "and media estimated."
210 PRINT
220 LOCATE 22, 1: PRINT TAB(25); "Press any key to begin."
230 a$ = INKEY$: IF LEN(a$) = 0 THEN 230
240 ' Default values
```

```
250 qs = 20: t1 = 15: t2 = 15: c1 = 20: ss1 = .8: ss2 = 0:
rh1 = .5: rh2 = 1: d1 = 36: Ip = 2: vp = 120: np = 1: timp =
24:
260 '
270 Iff = 2: vff = 120: nf = 1: timf = 24: pe = .11: pw =
.012: pm = 20: MC1 = 50: RT1 = 10
280 '
290 '
300 ' Entry point for changing data
310 '
320 CLS : GOSUB 3530: GOSUB 3590: 'Print header and input
screen
330 '
340 ' Interactively change values using a standard input
subroutine:
350 ' S6$ = default value  S1,S2=screen location   S3=1 is
numeric input
360 ' S4,S5=range          S9=length of input      S3=3 is
Y/N answer
370 ' S returns answer     S$ returns Y/N
380 '      In some cases, the default value is replaced with
an integer
390 '
400 'corresponding with a menu on line twenty three.
410    ' qs
420 S6$ = STR$(qs): S1 = 5: S2 = 60: S3 = 1: s4 = 0: S5 =
3000: S9 = 4: GOSUB 4020: qs = s
430    ' t1
440 S6$ = STR$(t1): S1 = 7: S2 = 60: S3 = 1: s4 = 0: S5 =
35: S9 = 4: GOSUB 4020: t1 = s
450    ' t2
460 S6$ = STR$(t2): S1 = 9: S2 = 60: S3 = 1: s4 = 0: S5 =
35: S9 = 4: GOSUB 4020: t2 = s
470    ' c1
480 S6$ = STR$(c1): S1 = 11: S2 = 60: S3 = 1: s4 = 0: S5 =
90: S9 = 4: GOSUB 4020: c1 = s
490    'ss1
500 S6$ = STR$(ss1): S1 = 13: S2 = 60: S3 = 1: s4 = 0: S5 =
1: S9 = 4: GOSUB 4020: ss1 = s
510    'ss2
520 S6$ = STR$(ss2): S1 = 15: S2 = 60: S3 = 1: s4 = 0: S5 =
1: S9 = 4: GOSUB 4020: ss2 = s
530    'rh1
540 S6$ = STR$(rh1): S1 = 17: S2 = 60: S3 = 1: s4 = 0: S5 =
100: S9 = 4: GOSUB 4020: rh1 = s
550    'rh2
```

```
560 S6$ = STR$(rh2): S1 = 19: S2 = 60: S3 = 1: s4 = 0: S5 =
100: S9 = 4: GOSUB 4020: rh2 = s
570   'd1
580 S6$ = STR$(d1): S1 = 21: S2 = 60: S3 = 1: s4 = 0: S5 =
360: S9 = 4: GOSUB 4020: d1 = s
590   'Ip
600 S6$ = STR$(Ip): S1 = 23: S2 = 60: S3 = 1: s4 = 0: S5 =
15: S9 = 4: GOSUB 4020: Ip = s
610   'vp
620 S6$ = STR$(vp): S1 = 25: S2 = 60: S3 = 1: s4 = 0: S5 =
220: S9 = 4: GOSUB 4020: vp = s
630   'timp
640 S6$ = STR$(timp): S1 = 27: S2 = 60: S3 = 1: s4 = 0: S5 =
24: S9 = 4: GOSUB 4020: timp = s
650   'np
660 S6$ = STR$(np): S1 = 29: S2 = 60: S3 = 1: s4 = 0: S5 =
10: S9 = 4: GOSUB 4020: np = s
670   'Iff
680 S6$ = STR$(Iff): S1 = 31: S2 = 60: S3 = 1: s4 = 0: S5 =
15: S9 = 4: GOSUB 4020: Iff = s
690   'vff
700 S6$ = STR$(vff): S1 = 33: S2 = 60: S3 = 1: s4 = 0: S5 =
220: S9 = 4: GOSUB 4020: vff = s
710   'timf
720 S6$ = STR$(timf): S1 = 35: S2 = 60: S3 = 1: s4 = 0: S5 =
24: S9 = 4: GOSUB 4020: timf = s
730   'nf
740 S6$ = STR$(nf): S1 = 37: S2 = 60: S3 = 1: s4 = 0: S5 =
20: S9 = 4: GOSUB 4020: nf = s
750   'pe
760 S6$ = STR$(pe): S1 = 39: S2 = 60: S3 = 1: s4 = 0: S5 =
.11: S9 = 4: GOSUB 4020: pe = s
770   'pw
780 S6$ = STR$(pw): S1 = 41: S2 = 60: S3 = 1: s4 = 0: S5 =
.11: S9 = 4: GOSUB 4020: pw = s
790   'pm
800 S6$ = STR$(pm): S1 = 43: S2 = 60: S3 = 1: s4 = 0: S5 =
40: S9 = 4: GOSUB 4020: pm = s
801   'MC1
802 S6$ = STR$(MC1): S1 = 45: S2 = 60: S3 = 1: s4 = 20: S5 =
50: S9 = 4: GOSUB 4020: MC1 = s
803   'RT1
804 S6$ = STR$(RT1): S1 = 47: S2 = 60: S3 = 1: s4 = 5: S5 =
20: S9 = 4: GOSUB 4020: RT1 = s
810 '
820 '                                   Check if values OK
```

```
830 COLOR 0, 7: LOCATE 4, 1: PRINT "CHANGE VALUES  (Y/N)?";
TAB(30); "N"
840 S6$ = "N": S1 = 4: S2 = 30: S3 = 3: S9 = 7: GOSUB 4020:
IF s$ = "Y" THEN 410
850 CLS : GOSUB 3530: LOCATE 12, 12: PRINT
860 '

'870 OPEN "output.txt" FOR OUTPUT AS #1

890 '
900 'Calculate temperature based on farenhite degree.
910 '
920 'PRINT "the average temperature at the inlet and outlet
of the biofilters is used as the biofilter temperature (t)
but in this"
940 '
950 'PRINT "this experiment there were not significant
differents between temperatures at the in let and outlets."
960 '
970 'PRINT "tf1 and tf2 is used for quantitative calculation
of the amount of ammonia."
980 '
990 'PRINT "t is used for calculation of the effect of the
temperature."
1000 t = (t1 + t2) / 2
1005 '
1010 tf = (9 * t + 160) / 5
1020 '
1030 tf1 = (9 * t1 + 160) / 5
1035 '
1040 tf2 = (9 * t2 + 160) / 5
1050 '
1060 'Calculate one pound mole of ammonia at tf1 and tf2
degree farenhite
1070 vt1 = 1 * .73 * (460 + tf1)
1080 vt2 = 1 * .73 * (460 + tf2)
1090 PRINT "One pound mole of ammonia at tf1 degree (F)";
TAB(50); USING "###.#"; vt1; : PRINT TAB(56); "Ib-mol"
1100 PRINT
1110 PRINT "one pound mole of ammonia at tf2 degree (F)";
TAB(50); USING "###.#"; vt2; : PRINT TAB(56); "Ib-mol"
1120 PRINT
1130 'Calculate the effect of temperature
1140 'PRINT "a is the effect of the temperature on the
microbial activity"
1150 e = 2.718
1155 a = 1
```

```
1160
1170 GOTO 3830: 'OUTPUT
1180 '
1190 '
1200 'cgi is the mass of ammonia goes to the pilot scale
biofilters per day.
1210 'cgo is the mass of ammonia goes out of the pilot scale
biofilter.
1220 'EC is the elimination capacity of the pilot scale
biofilters (normalized factor of volume airflow and time
normally explain as g/m3/h.
1230 'ECt is the elimination capacity normalized with the
effect of temperature.
1240 'In this predictive model the unit of EC is g/m3/d.
1250 'q1 is the volume of air pass through the pilot scale
biofilters per day (L/d).
1260 'vf is the volume of the pilot sacale biofilter m3.
1270 'Empty bed retention time (EBRT) for the pilot sacle
biofilters.
1280 'EBRT1 is predicted retention time for treating the
available contaminated air based on eliminating ammonia to
zero ppm.
1290 'Removal efficiency (RE)of ammonia in the pilot scale.
1300 'vfs is the volume of the material (expanded
polystyrene) in the bioscrubber m3
1310 'Total average of the retention time in the pilot
scale=(vf*1000)/q+(vfs*1000)/(4*q)=(150/19)+(325/(4*19)=12.1
6 second.
1320 'V1 is the predicted volume of the course compost over
1 inches size needed for treating Qs liters polluted air
(m3).
1330 'cgit is the mass of ammonia for treating per day
available in the source malodourous air.
1340 'cgot is the mass of ammonia that should go out from
the biofilter with 10 second retention time.
1350 q = 19
1360 q1 = 86400 * q
1370 'PRINT "EC = (c1-c2)*q1/Vf=(cgi-cgo)/vf"
1380 IF c1 >= 3 AND c1 <= 40 THEN RE = -1.67 * c1 + 106.67
1390 c2 = (100 - RE) * c1 / 100
1400 IF ss1 > 1 THEN END
1410 'PRINT "pridiction of cgi, cgo, EC, pH, EBRT, RE in the
pilot scale"
1420 '
1430 vfs = .325
```

```
1440 'calculate the mass of ammonia at the inlet (with c1
ppmv and t1 celcius) and outlet of biofilters (with c2 ppmv
and t2 celcius)
1515 'IF c1 >= 0 AND c1 <= 45 THEN pH =
1520 'calculation of empty bed retention time (EBRT)
1530 vf = .15
1540 EBRT = vf * 1000 / q
1550 '
1560 '
'1565 PRINT c1; ss1; qs; vt1; cgit: END
1570
     '
1580 '
1590 '
1600 PRINT "Mass of ammonia (in) pilot scale (cgi)",
TAB(50); USING "###.#"; cgi; : PRINT TAB(56); "(g/d)"
1610 PRINT
1620 PRINT "Mass of ammonia (out) pilot scale (cgo)",
TAB(50); USING "###.#"; cgo; : PRINT TAB(56); "(g/d)"
1630 PRINT
1640 PRINT "Elimination capacity (EC)", TAB(50); USING
"###.#"; EC; : PRINT TAB(56); "(g/m3/d)"
1650 PRINT
1660 PRINT "Elimination capacity with effect of temp (ECt)";
TAB(50); USING "###.#"; ECt; : PRINT TAB(56); "(g/m3/d)"
1670 PRINT
1680 PRINT "predicted pH value", TAB(50); USING "###.#"; pH
1690 PRINT
1700 PRINT "Empty bed retention time (EMRT)", TAB(50); USING
"###.#"; EBRT; : PRINT TAB(56); "s"
1710 PRINT
1720 PRINT "Predicteed retention time minimum (EBRT1)",
TAB(50); USING "###.#"; EBRT1; : PRINT TAB(56); "s"
1730 PRINT
1740 PRINT "Removal efficiency (RE)", TAB(50); USING
"###.#"; RE; : PRINT TAB(56); "%"
1742 PRINT
1745 PRINT "Ammonia concentration at outlet (c2)", TAB(50);
USING "###.#"; c2; : PRINT TAB(56); "ppm"
1750 PRINT
1760 PRINT "Mass of ammonia available in the polluted gas";
TAB(49); USING "####.#"; cgit; : PRINT TAB(56); "(g/d)"
1770 PRINT
1780 PRINT "Minimum volume of course compost needed";
TAB(50); USING "###.#"; V1; : PRINT TAB(56); "m3"
1790 PRINT
```

```
1800 PRINT "Mass of ammonia at the outlet with 10s EBRT";
TAB(49); USING "####.#"; cgot; : PRINT TAB(56); "(g/d)"
1810 '
1820
1825 IF c1 >= 90 THEN PRINT "NH3 overlimit!!!!!": END
1830 x1 = c1
1840 '
1850 '
1860 '
1870 '
1880 '
1890 '
1900 '
1910 '
'1920 PRINT #1, "Amount of ammonia gas inter to the
biofilter,", cgi, ",g/m3/d"
1925 PRINT
1930 PRINT "Temperature effect", TAB(50); USING "###.#"; a
'To Screen
'1935 PRINT #1, "Temperature effect", TAB(50); USING
"###.#"; a 'To File
1940 PRINT
1950 PRINT
1960 PRINT "NH3-N in", TAB(50); USING "###.#"; y1; : PRINT
TAB(56); "g/m3/d"
1970 PRINT
1980 PRINT "NH3-N out", TAB(50); USING "###.#"; y2; : PRINT
TAB(56); "g/m3/d"
1990 PRINT
2000 PRINT "Unknown-N", TAB(50); USING "###.#"; y3; : PRINT
TAB(56); "g/m3/d"
2010 PRINT
2020 PRINT "Nitrite-N", TAB(50); USING "###.#"; y4; : PRINT
TAB(56); "g/m3/d"
2030 PRINT
2040 PRINT "Nitrate-N", TAB(50); USING "###.#"; y5; : PRINT
TAB(56); "g/m3/d"
2050 PRINT
2060 '
2061 'Assumption all NH3-N eliminate to nitrite and nitrate.
2062 PRINT "Volume of media based on NO2-N and NO3-N
production", TAB(50); USING "###.##"; V2; : PRINT TAB(56);
"m3"
2063 PRINT "Empty bed retention time maximum (EBRT2)",
TAB(50); USING "###.#"; EBRT2; : PRINT TAB(56); "s"
2070 '
2080 PRINT : PRINT "Press key to proceed"; : INPUT X: CLS
```

```
2090 '
2100 '
2110 'Calculation of amount of water needed for humidifier
2420 '
2430 PRINT "Amount of water available in the inlet air per
day", : PRINT W1, : PRINT "m3/day"
2440 PRINT "Amount of water available in the outlet air per
day", : PRINT W2, : PRINT "m3/day"
2450 PRINT "Amount of water needed for humidifier per day",
: PRINT W, : PRINT "m3/day"
2455 PRINT "Predicted amount of water for controlling
Chemicals", : PRINT Wa, : PRINT "m3/day"
2460 'estimation of Nitrite Concentration
2470
2480 'N1=Nitrite concentration at average 14.78 Celsius
degree and average 2.08
2490 'N2=Nitrite concentration at average 14.78 Celsius
degree and average 21.35 ppm ammonia

2500 'N3=Nitrite concentration at average 14.78 Celsius
degree and average 45.07 ppm ammonia
2510 'N4=Nitrite concentration at average 14.78 Celsius
degree and average 87.25 ppm ammonia
2520
2530 'N1 =
2540 PRINT
2550 'N2 =
2560 PRINT
2570 'N3 =
2580 PRINT
2590 'N4 =
2600
2610 PRINT "NO2 with 2.08 ppm NH3 and 14.78 Celsius", :
PRINT N1, : PRINT "ppm"
2620 PRINT "NO2 with 21.35 ppm NH3 and 14.78 Celsius", :
PRINT N2, : PRINT "ppm"
2630 PRINT "NO2 with 45.08 ppm NH3 and 14.78 Celsius", :
PRINT N3, : PRINT "ppm"
2640 PRINT "NO2 with 87.25 ppm NH3 and 14.78 Celsius", :
PRINT N4, : PRINT "ppm"
2650 c3 = 2.08
2660 c4 = 21.35
2670 c5 = 45.08
2680 c6 = 87.25
2690 'ma=slope of the line
2700 'ma = (N2 - N1) / (c4 - c3)
2710 'IF c1 >= 2.08 AND c1 <= 21.35 THEN ya =
```

```
2720
2730 'mb = (N3 - N2) / (c5 - c4)
2740 'IF c1 > 21.35 AND c1 <= 45.08 THEN yb =
2750
2760 'MC = (N4 - N3) / (c6 - c5)
2770 'IF c1 > 45.08 AND c1 <= 87.25 THEN yc =
2780 'IF c1 > 87.25 THEN GOTO 2060
2790 'IF d1 >= 0 AND d1 <= 36 THEN ya =
2800 PRINT "predicted NO2 with c1 ppm NH3 and t celsius at
day"; : PRINT d1
2810 PRINT ya, : PRINT "ppm"
2820 PRINT yb, : PRINT "ppm"
2830 PRINT yc, : PRINT "ppm"
2840 PRINT
2850 'estimation of Nitrate Concentration
2860 'O1=Nitrate concentration at average 14.78 Celsius
degree and average 2.08
2870 'O2=Nitrate concentration at average 14.78 Celsius
degree and average 21.35 ppm ammonia
2880 'O3=Nitrate concentration at average 14.78 Celsius
degree and average 45.07 ppm ammonia
2890 'O4=Nitrate concentration at average 14.78 Celsius
degree and average 87.25 ppm ammonia
2900 'IF d1 >= 0 AND d1 <= 30 THEN O1 =
2910 'O1 =
2920 PRINT
2930 'O2 =
2940 PRINT
2950 'O3 =
2960 PRINT
2970 'O4 =
2980
2990 PRINT "NO3 with 2.08 ppm NH3 and 14.78 Celsius", :
PRINT O1, : PRINT "ppm"
3000 PRINT "NO3 with 21.35 ppm NH3 and 14.78 Celsius", :
PRINT O2, : PRINT "ppm"
3010 PRINT "NO3 with 45.08 ppm NH3 and 14.78 Celsius", :
PRINT O3, : PRINT "ppm"
3020 PRINT "NO3 with 87.25 ppm NH3 and 14.78 Celsius", :
PRINT O4, : PRINT "ppm"
3030 'md=slope of the line
3040 'md = (O2 - O1) / (c4 - c3)
3050 'IF c1 >= 2.08 AND c1 <= 21.35 THEN yd =
3060
3070 'me = (O3 - O2) / (c5 - c4)
3080 'IF c1 > 21.35 AND c1 <= 45.08 THEN ye =
3090
```

```
3100 'mf = (O4 - O3) / (c6 - c5)
3120 'IF c1 > 45.08 AND c1 <= 87.25 THEN yf =
3130 'IF c1 > 87.25 THEN GOTO 2060
3140  'IF d1 >= 0 AND d1 <= 36 THEN yd =
3150 PRINT "predicted NO3 with c1 ppm NH3 and t1 celsius at
day d1:"
3160 PRINT yd, : PRINT "ppm"
3170 PRINT ye, : PRINT "ppm"
3180 PRINT yf, : PRINT "ppm"
3190 'estimation of biofilter cost (Assumption all pumps and
fans are the same)
3200 '1- Capital Cost
3210 'Tcm = V2 * pm
3220
3230 PRINT ; "Cost of coarse compost media", TAB(52); USING
"###.##"; Tcm; : PRINT TAB(60); "CN$"
3240 '2- Operating Cost
3250
3260 '2-1 Cost of electricity
3270 'power(watt)=V*I
3280 'Ip=Amper of the pump
3290 'vp=voltage of the pump Power = Po = Vp * Ip(watt)
3300 'Timp=Hours that pumps are working per day
3310 'np=number of pumps are working
3320 'Iff=Amper of fans
3330 'vff=voltage of the fan
3340 'Timf=Hours that fans are working per day
3350 'nf=number of fans are working per day
3360 'pe=price of electricity per kwh
3370 'pw=price of water per m3
3380 'pm=price of media per m3
3390 'TEP=Total electricity price per day (Canadian dollars)
3400 '
3410 'TEP = (vp * Ip * timp * np + Iff * vff * timf * nf) *
pe / 1000
3420
3430 PRINT ; "The cost of electricity per day", TAB(52);
USING "###.##"; TEP; : PRINT TAB(60); "CN$"
3440 '2-2 Cost of water
3450 'Price of water=1.2 cents/gal Gallon (Canadian)=4.54
Liter
3460 'Tpw = (W * 1000 + V2 * 18.1) / 4.54 * pw
3470 PRINT "The cost of water per day", TAB(52); USING
"###.##"; Tpw; : PRINT TAB(60); "CN$"
3480
3490 PRINT : PRINT TAB(15); : PRINT "Press 1 to quit; 2 to
change values"; : INPUT X
```

```
3500 IF X = 1 THEN END
3510 CLS
3520 GOTO 300 'End of program.  Go back to beginning to
start another iteration.
3530 '
3540 ' Clear screen and Print Header
3550 '
3560 CLS : COLOR 0, 7: PRINT TAB(17); "A BIOFILTRATION MODEL
FOR AGRICULTURE FACILITIES"; ""
3570 PRINT TAB(17); "                                    ": COLOR
7, 0: PRINT
3580 RETURN
3590 '
3600 ' Print screen of input data
3610 '
3620 PRINT : PRINT TAB(10); "Available polluted airflow
(L/s)"; TAB(60); qs
3630 PRINT : PRINT TAB(10); "Temperature at the inlet of
biofilter (C)"; TAB(60); t1
3640 PRINT : PRINT TAB(10); "Temperature at the outlet of
biofilter (C)"; TAB(60); t2
3650 PRINT : PRINT TAB(10); "Ammonia concentration of the
polluted air (ppm)"; TAB(60); c1
3660 PRINT : PRINT TAB(10); "Hydrogen sulfide concentration
at the inlet "; TAB(60); ss1
3670 PRINT : PRINT TAB(10); "Hydrogen sulfide concentration
at the outlet"; TAB(60); ss2
3680 PRINT : PRINT TAB(10); "Relative humidity of air at the
inlet (%)"; TAB(60); rh1
3690 PRINT : PRINT TAB(10); "Relative humidity of air at the
outlet (%)"; TAB(60); rh2
3700 PRINT : PRINT TAB(10); "Days of operating after 14 days
of starting"; TAB(60); d1
3710 PRINT : PRINT TAB(10); "Amper of the pump"; TAB(60); Ip
3720 PRINT : PRINT TAB(10); "Voltage used for the pump";
TAB(60); vp
3730 PRINT : PRINT TAB(10); "Time that pumps are working (h)
per day"; TAB(60); timp
3740 PRINT : PRINT TAB(10); "Number of fans are working per
day"; TAB(60); np
3750 PRINT : PRINT TAB(10); "Amper of one of the fans";
TAB(60); Iff
3760 PRINT : PRINT TAB(10); "Voltage of one of the fans";
TAB(60); vff
3770 PRINT : PRINT TAB(10); "Time that fans are working
(h)"; TAB(60); timf
```

```
3780 PRINT : PRINT TAB(10); "Number of fans are working per
day"; TAB(60); nf
3790 PRINT : PRINT TAB(10); "Price of electricity/kwh";
TAB(60); pe
3800 PRINT : PRINT TAB(10); "Price of water (CN $/ galon)";
TAB(60); pw
3810 PRINT : PRINT TAB(10); "Price of media per m3";
TAB(60); pm
3811 PRINT : PRINT TAB(10); "Moisture content of media %";
TAB(60); MC1
3812 PRINT : PRINT TAB(10); "Retention time second";
TAB(60); RT1
3820 RETURN
3830 '
3840 ' Output
3850 '
3860 CLS : GOSUB 3530: GOSUB 1200 ' Print page one
3870 LOCATE 4, 1: COLOR 0, 7: PRINT "Press any key to see
more OUTPUT"
3880 COLOR 7, 0: a$ = INKEY$: IF LEN(a$) = 0 THEN 3880
3890 'CLS : GOSUB 3140    ' Print page two of initial output
3900 'LOCATE 23, 1: COLOR 0, 7: PRINT "Press any key to see
more OUTPUT"

3910 'COLOR 7, 0: a$ = INKEY$: IF LEN(a$) = 0 THEN 3910
3920 'CLS : GOSUB 3530    'Print energy partition
3930 'LOCATE 23, 1: COLOR 0, 7: PRINT "Press any key to see
more OUTPUT"
3940 'COLOR 7, 0: a$ = INKEY$: IF LEN(a$) = 0 THEN 3940
3950 'CLS : GOSUB 3770
3960 '    CHANCE TO RERUN OR end
3970 COLOR 0, 7: LOCATE 23, 1: PRINT "CHANGE INPUT VALUES
(Y/N)?"; TAB(30); "Y"
3980 S6$ = "Y": S1 = 23: S2 = 30: S3 = 3: S9 = 7: GOSUB
4020: IF s$ = "Y" THEN 1820
3990 CLS : CLEAR
4000 END
4010
4020 ' INPUT SUBROUTINE
4030 '
4040 '     S1,S2=POSITION  S3: 1=Numeric 2=String 3=Y/N
S6$,S$=IN,OUT
4050 '     S4,S5 = Range    S9 = Length
4060 s$ = ""
4070 GOSUB 4190: PRINT SPC(LEN(s$));
4080 S8 = FALSE: GOSUB 4190: GOSUB 4200: GOSUB 4220: GOSUB
4380
```

```
4090 IF s$ = "" THEN s$ = S6$: GOTO 4110
4100 IF S3 = 1 THEN GOSUB 4400: IF S8 = TRUE THEN 4070
4110 IF S3 = 1 THEN GOSUB 4520: IF S8 = TRUE THEN 4070
4120 IF S3 = 3 THEN GOSUB 4570: IF S8 = TRUE THEN 4070
4130 IF S3 = 1 THEN s = VAL(s$)
4140 'COLOR 7, 0
4141 LOCATE 46, 1, 0
4142 PRINT TAB(80);
4143 LOCATE , , 1
4150 DEF SEG = 0: POKE 1050, PEEK(1052): DEF SEG : POKE 106,
0'Clear buffers
4160 RETURN
4170 '
4180 LOCATE S1, S2, 1: RETURN          'POSITION CURSOR
VISIBLE
4190 LOCATE S1, S2, 0: RETURN          'POSITION CURSOR
INVISIBLE
4200 PRINT S6$; : GOSUB 4180: RETURN 'PRINT DEFAULT
4210 '
4220 s$ = ""                           'TRANSPARENT CURSOR
ROUTINE
4230 S1$ = INPUT$(1)
4240 s = ASC(S1$): IF s <> 13 GOTO 4280
4250 IF s$ = "" THEN GOSUB 4190: GOSUB 4200: RETURN
4260 IF LEN(s$) < LEN(S6$) THEN PRINT SPC(LEN(S6$) -
LEN(s$));
4270 RETURN
4280 IF s < 32 GOTO 4340
4290 IF s = 34 THEN S1$ = "'"
4300 s$ = s$ + S1$
4310 PRINT S1$; : IF S9 > 0 AND LEN(s$) > S9 THEN 4350
4320 IF LEN(s$) = 1 THEN GOSUB 4190: PRINT SPC(S9); : GOSUB
4180: PRINT s$;
4330 GOTO 4230
4340 IF LEN(s$) < 1 GOTO 4220
4350 IF LEN(s$) = 1 THEN PRINT CHR$(29); " "; CHR$(29); :
GOTO 4220
4360 s$ = LEFT$(s$, LEN(s$) - 1): PRINT CHR$(29); " ";
CHR$(29); : GOTO 4230
4370 '
4380 IF s$ = "<" THEN CLS : PRINT "NORMAL EXIT"; : CLS :
LOCATE , , 1: END ELSE RETURN
4390 '
4400 S1$ = s$: S7 = 0                                  'CHECK
FOR NUMERIC INPUT
4410 IF LEFT$(S1$, 1) = " " THEN S1$ = RIGHT$(S1$, LEN(S1$)
- 1): GOTO 4410
```

```
4420 IF RIGHT$(S1$, 1) = " " THEN S1$ = LEFT$(S1$, LEN(S1$)
- 1): GOTO 4420
4430 IF LEN(S1$) < 1 GOTO 4480
4440 FOR s = 1 TO LEN(S1$): S6 = ASC(MID$(S1$, s, 1))
4450 IF S6 >= 48 AND S6 <= 57 GOTO 4490
4460 IF (S6 = 43 OR S6 = 45) AND s = 1 THEN 4490
4470 IF S6 = 46 AND S7 = 0 THEN S7 = 1: GOTO 4490
4480 S2$ = "PLEASE ENTER NUMBERS ONLY": S1$ = "": GOSUB
4620: RETURN
4490 NEXT
4500 RETURN
4510 '
4520 S6 = VAL(s$)       'CHECK FOR PROPER LIMITS
4530 IF S6 < s4 THEN S2$ = "INPUT BELOW": S1$ = STR$(s4):
GOSUB 4620: GOTO 4550
4540 IF S6 > S5 THEN S2$ = "INPUT ABOVE": S1$ = STR$(S5):
GOSUB 4620
4550 RETURN
4560 '
4570 IF LEFT$(s$, 1) = "y" OR LEFT$(s$, 1) = "Y" THEN s$ =
"Y": GOTO 4600'Y/N ?
4580 IF LEFT$(s$, 1) = "n" OR LEFT$(s$, 1) = "N" THEN s$ =
"N": GOTO 4600
4590 S2$ = "PLEASE ANSWER EITHER YES OR NO": S1$ = "": GOSUB
4620
4600 RETURN
4610 '
4620 COLOR 31, 0, 0: BEEP: LOCATE 46, 1, 0'ERROR FOR ALL
CONDITIONS
4630 PRINT "     "; S2$; S1$; TAB(80); 'PRINT ERROR
4640 COLOR 7, 0, 0: S8 = TRUE
4650 RETURN
```

Appendix B: Measurement of the Airflow

In operating a biofilter it is helpful to understand the techniques used to deter mine air velocity. By multiplying air velocity (distance traveled per unit of time) by the cross section area of a duct, you can determine the air volume flowing past a point in the duct per unit of time. For measuring the volume of the contaminated air that pass throughout a biofilter two parameters should be measured including the cross section of the duct and velocity of the contaminated air. The cross section of the duct easily can be considered with the measurement of the size of the duct but for measuring the velocity different methods are available such as using manometer together with pitot tube. Most manometer scales are calibrated in inches of water. Using readings from such an instrument, the air velocity can be calculated using the following formulas (Dwyer Instruments 2002).

$$V = 1.413\sqrt{\frac{h_v}{d}} \qquad \text{(B-1)}$$

Where: V = Velocity in m/s. h_v = Velocity pressure in Pa. d = Density of air in kg/m^3.

To determine dry air density, use the formula:

$$d = 0.0063 \times \frac{P_B}{T} \qquad \text{(B-2)}$$

Where: P_B = Barometric (or absolute) static pressure in Pa. T = Absolute temperature = $1.8 \times T_1 + 492$ Where: T_1 = temperature of the air (°C).

Once the average air velocity is known, the airflow rate can be computed using the formula:

$$Q = A \times V \qquad \text{(B-3)}$$

Where: Q = Amount of airflow in (m^3/s). A = Cross sectional area (m^2). V = Average velocity in (m/s).

However, in the primary experiment the velocity pressure measured through the experiment and then air flow calculated with the following condition.

$C = 15\ °C$ P_B=93099.75 Pa

$T = 1.8°C + 460 = 519$ $A = 0.019$ m^2.

$$d = 0.0063 \times \frac{P_B}{T} = 1.13 \text{ kg/m}^3 \qquad \text{(B-4)}$$

With combination of equations 1, 2, and 3 the airflow can be calculated.

Appendix B.1 The airflow, velocity pressure and pressure drop through filter 1 (F1)

Day	Vel. P. (hv) In. of water	Vel. P. (hv) Pa	Velocity (V) m/s	Airflow L/s	P. drop In. of H_2O	P. drop (Pa)
1	0.035	8.71	3.92	75	7.8	1941
3	0.03	7.47	3.63	69	8.1	2016
4	0.03	7.47	3.63	69	8.1	2016
6	0.03	7.47	3.63	69	8	1991
8	0.02	4.98	2.97	56	8.1	2016
10	0.03	7.47	3.63	69	7.5	1866
12	0.02	4.98	2.97	56	8.1	2016
13	0.02	4.98	2.97	56	8.8	2190
14	0.015	3.73	2.57	49	8.8	2190
15	0.015	3.73	2.57	49	8.6	2140
18	0	0.00	0.00	0	8.2	2040
19	0.01	2.49	2.10	40	8.2	2040
20	0.005	1.24	1.48	28	7.4	1841
21	0.005	1.24	1.48	28	7.4	1841
23	0	0.00	0.00	0	8.4	2090
24	0.015	3.73	2.57	49	7.4	1841
25	0.025	6.22	3.32	63	7.4	1841
26	0.01	2.49	2.10	40	7.2	1792
27	0	0.00	0.00	0	7	1742
28	0.06	14.93	5.14	98	2	498
32	0.08	19.91	5.93	113	2	498
35	0.07	17.42	5.55	105	2.8	697
38	0.095	23.64	6.46	123	2.8	697
40	0.07	17.42	5.55	105	2.6	647
42	0.065	16.17	5.35	102	2.6	647
46	0.085	21.15	6.11	116	2	498

49	0.075	18.66	5.74	109	1.8	448
53	0.06	14.93	5.14	98	2.1	523
54	0.07	17.42	5.55	105	2.2	547
56	0.065	16.17	5.35	102	2.2	547
61	0.08	19.91	5.93	113	2.4	597
63	0.075	18.66	5.74	109	2.4	597
66	0.07	17.42	5.55	105	2.2	547
67	0.08	19.91	5.93	113	2	498
69	0.07	17.42	5.55	105	2.2	547
76	0.07	17.42	5.55	105	2.2	547
81	0.075	18.66	5.74	109	2.6	647
83	0.08	19.91	5.93	113	2.6	647
90	0.08	19.91	5.93	113	2.4	597

Appendix B.2 The air flow velocity pressure and pressure drop thoughout the biofilter 2 (F2)

Day	Vel. P. (hv) In. of H_2O	Vel. P. (hv) Pa	Velocity (V) m/s	Airflow L/s	P. drop In. of H_2O	P. drop (Pa)
1	0.06	14.93	5.14	98	5.2	1294
3	0.06	14.93	5.14	98	5.4	1344
4	0.055	13.69	4.92	93	6.2	1543
6	0.05	12.44	4.69	89	6.6	1642
8	0.03	7.47	3.63	69	4.8	1194
10	0.04	9.95	4.19	80	6.4	1593
12	0.04	9.95	4.19	80	6	1493
13	0.035	8.71	3.92	75	4.2	1045
14	0.035	8.71	3.92	75	4.4	1095
15	0.03	7.47	3.63	69	4.4	1095
18	0.03	7.47	3.63	69	8	1991

19	0.035	8.71	3.92	75	4.6	1145
20	0.04	9.95	4.19	80	4.2	1045
21	0.04	9.95	4.19	80	4.2	1045
23	0.07	17.42	5.55	105	4.2	1045
24	0.05	12.44	4.69	89	3.4	846
25	0.04	9.95	4.19	80	3.2	796
26	0.05	12.44	4.69	89	4	995
27	0.08	19.91	5.93	113	4.2	1045
28	0.1	24.88	6.63	126	2.2	547
32	0.1	24.88	6.63	126	2.6	647
35	0.1	24.88	6.63	126	2.6	647
38	0.08	19.91	5.93	113	2.8	697
40	0.07	17.42	5.55	105	2.9	722
42	0.09	22.40	6.29	120	3.9	970
46	0.08	19.91	5.93	113	4	995
49	0.09	22.40	6.29	120	4.4	1095
53	0.075	18.66	5.74	109	2.6	647
54	0.65	161.75	16.91	321	2.8	697
56	0.07	17.42	5.55	105	3.4	846
61	0.065	16.17	5.35	102	3.2	796
63	0.055	13.69	4.92	93	3.8	946
66	0.05	12.44	4.69	89	4.2	1045
67	0.045	11.20	4.45	85	4	995
69	0.04	9.95	4.19	80	4.4	1095
76	0.035	8.71	3.92	75	6	1493
81	0.025	6.22	3.32	63	6.2	1543
83	0.01	2.49	2.10	40	6.5	1617
90	0.005	1.24	1.48	28	7.2	1792

Refrence: Dwyer Instruments, Inc. 2002. Controls & Gages Catalogue. P.O. Box 373/Michigan city, Indiana 46361.

Appendix C: An Example of Estimation of Mass of Ammonia and Sulfuric Acid

A pilot scale biofilter with 0.150 m^3 media is operating with 20 L/s polluted airflow and the concentration of ammonia is 20 ppmv. Estimate the daily consumption of the sulfuric acid required to neutralize the ammonia in a wet scrubber before going through the biofilter. Stimulate the amount of acid needed for a biofilter with 1 m^3 media to operate with the same condition of the pilot scale biofilter.

Assumption: retention time is enough for combining ammonia with acid solution.

Temperature of polluted gas = 20°C

Solution:

$$V1=\frac{(1)(0.730)(492+1.8\times 20)}{(1)(272.12)}=1.42\ \text{L} \qquad \text{(C-1)}$$

$$V = 8.64 \times 10^4 \times Q = 17.28 \times 10^5\ \text{L/d} \qquad \text{(C-2)}$$

$$\text{Mass of ammonia} = \frac{V \times C}{10^6 \times V_1} = \frac{17.28\times 10^5 \times 20}{10^6 \times 1.42} = 24.3\ \text{g/d} \qquad \text{(C-3)}$$

Mass of ammonia/m^3 media/d = 24.3/0.150 = 162 g/d

The molecular weight of H_2SO_4 is 2(1) + (32) +4(16) = 98.

The required quantity of sulfuric acid is calculated from the following equation

$$\text{Mass of needed sulfuric acid based} = \frac{98\times NH_3(g/d)}{2\times 17} = 70\ \text{g/d} \qquad \text{(C-4)}$$

Mass of sulfuric acid/m^3- media/d = 70/0.150 = 467 g/d.

Where:

V_1= the volume for 1 g of gas (ammonia) at °C temperature of polluted air (L)

m = 1 g

P=1 atmospheric pressure

R=0.730 (the universal gas constant)

T= absolute temperature, = 492 + 1.8×T_1 (gas temperature)

T_1 = temperature of the contaminated air (°C) (Haug, 1993)

Determine the volume of the polluted air with measurement of the airflow:

V = Volume of polluted air per day (L/d) = $60 \times 60 \times 24 \times Q = 8.64 \times 10^4 \times Q$

Q = average airflow pass through the biofilter (L/s) =20 L/s

C = ammonia concentration (ppmv)

Appendix D: Microbiological Analysis

At the end of the experiment with sulfuric acid eight samples took place from bioscrubbers and biofilters media. The samples were analysed by Alberta Reaserch council miocrobiological lab at Vegrevil and the analytical results are shown in Table D-1. The colony forming units (CFU) of *Thiobacillus* spp. responsible for the eliminating the H_2S in the bioscrubber media with using sulfuric acid was much higher than the CFU of the other bioscrubber media with no acid. It makes sense because this microorganism can grow better in acidic environment.

Appendix D.1 Microbiological analysis for enumeration of the Heterotrophic bacteria and Thiobacillus spp.

Sample #	Sample Information	Test type	Result (CFU[a]/g wet weight)
M01 - 175	1 SCR 2 No acid	HPC	2.2E+06
		Thiobacillus spp.	1.4E+03
M01 - 176	2 SCR1 Using Acid	HPC	2.7E+07
		Thiobacillus spp.	2.7E+06
M01 - 177	3 BF1 top	HPC	7.9E+07
		Thiobacillus spp.	1.8E+06
M01 - 178	4 BF1 middle	HPC	1.3E+07
		Thiobacillus spp.	1.1E+07
M01 - 179	5 BF1 bottom	HPC	9.3E+07
		Thiobacillus spp.	2.4E+06
M01 - 180	6 BF2 top	HPC	1.5E+08
		Thiobacillus spp.	7.4E+06
M01 - 181	7 BF2 middle	HPC	3.6E+08
		Thiobacillus spp.	1.6E+07
M01 - 182	8 BF2 bottom	HPC	9.0E+07
		Thiobacillus spp.	6.1E+06

Remarks:
Samples were weighed into a blender jar to which 90 mL of dilution buffer was added and then blended on high for 1 minute. This was further diluted, plated, and incubated. HPC counts were determined on R2A agar incubated for 7 days at 20°C. *Thiobacillus* spp. were enumerated on ATCC medium #238 incubated at 20°C for 18 days.
[a] = Colony forming units.

Appendix E: The Results of Multiple Regression Analysis

Assumption: RE = dependent variable and independent variables includes: pH, EC, NH_3-in (ppmv), total nitrite and nitrate washed out by water (TNoutbw) ($g/m^3/d$), total nitrite and nitrate produced per day (TNpgd) ($g/m^3/d$). However, all variables left in the model are significant at the 0.0500 levels. No other variable met the 0.0500 significance levels for entry into the model.

Appendix E.1 The results of multiple regration analysis for biofilter 2 with 20 ppm ammonia concentration

Variable	Parameter Estimate	Standard Error	Partial R-Square	P values
Intercept	73.83	5.32		< 0.0001
EC ($g/m^3/h$)	12.64	1.25	0.13	< 0.0001
NH_3in (ppm)	-3.00	0.36	0.28	< 0.0001
Total $NO_2^-+NO_3^-$ washed out (g/m3/d)	0.19	0.08	0.40	0.0240

Appendix E.2 The results of multiple regration analysis for biofilter with 45 ppm ammonia concentration

Variable	Parameter Estimate	Standard Error	Partial R-Square	P values
Intercept	84.30	6.42		< 0.0001
EC ($g/m^3/h$)	8.12	0.50	0.56	< 0.0001
NH_3in (ppm)	-2.02	0.20	0.30	< 0.0001

Appendix E.3 The results of multiple regration analysis for biofilter with 90 ppm ammonia concentration

Variable	Parameter Estimate	Standard Error	Partial R-Square	P values
Intercept	73.07	13.67		< 0.0001
pH	-3.29	1.25	0.0016	< 0.0406
EC ($g/m^3/h$)	3.53	0.36	0.93	< 0.0001
NH_3in (ppm)	-0.50	0.08	0.05	< 0.0001

Appendix F: Nitrogen Mass Balance Graphs

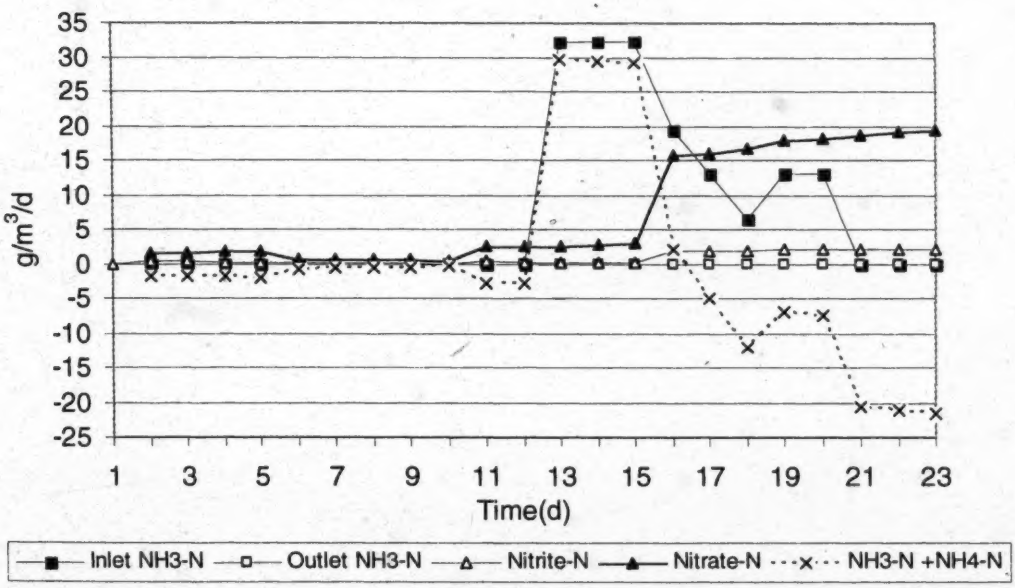


Figure F.1 Mass balance of nitrogen in the biofilter 1 trial 1 with no ammonia injection

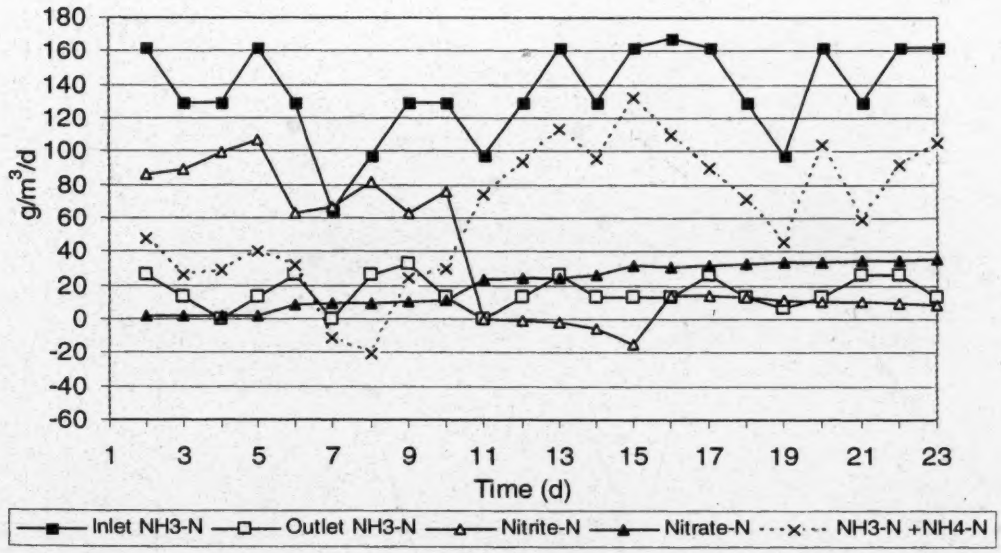


Figure F.2 Mass balance of nitrogen in the biofilter 2 trial 1 with 20 ppmv ammonia injection.

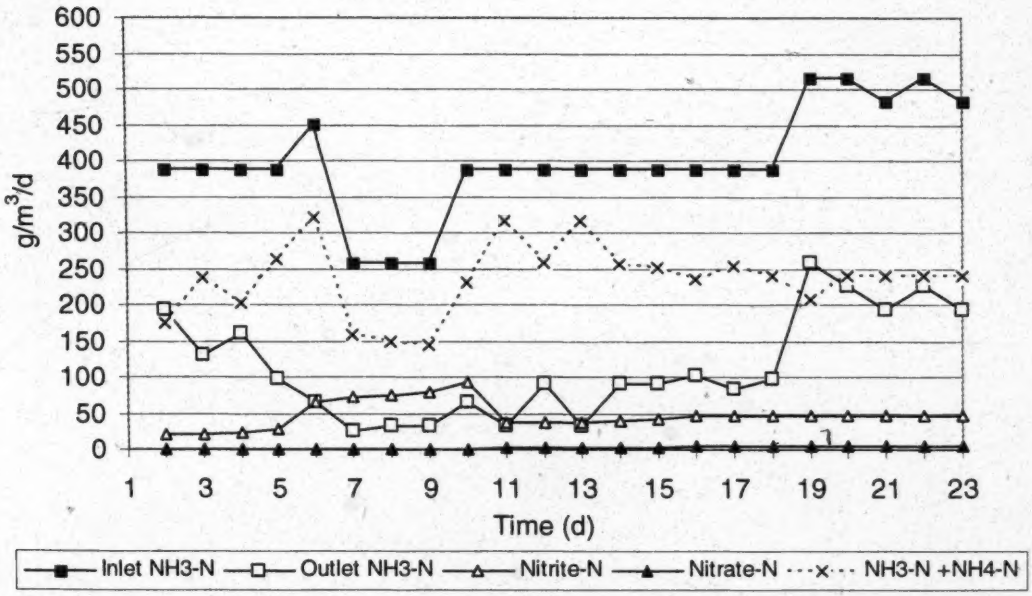


Figure F.3 Mass balance of nitrogen in the biofilter 3 trial 1 with 45 ppmv ammonia injection

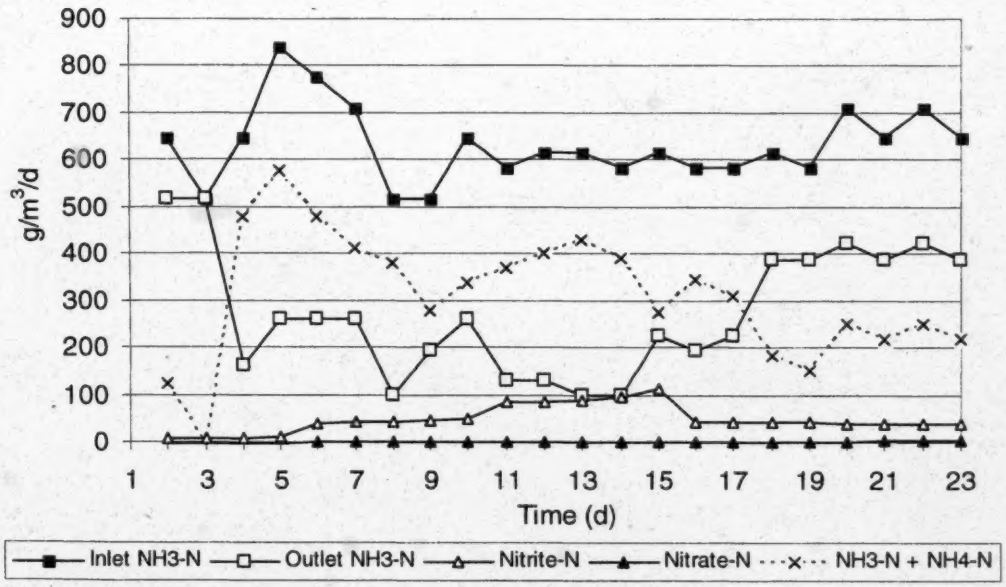


Figure F.4 Mass balance of nitrogen in the biofilter 4 trial 1 with 90 ppmv NH_3

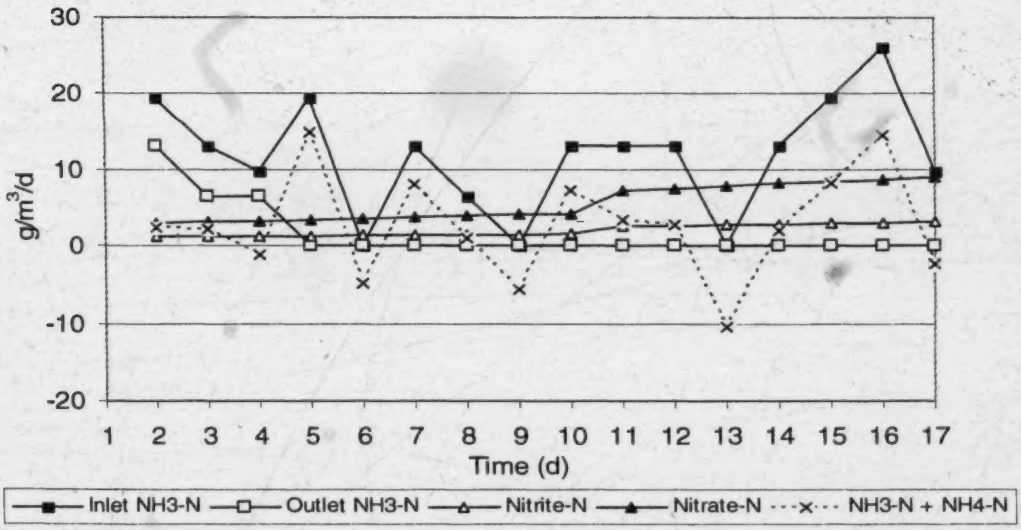


Figure F.5 Mass balance of nitrogen in the biofilter 1 trial 2 with no NH_3

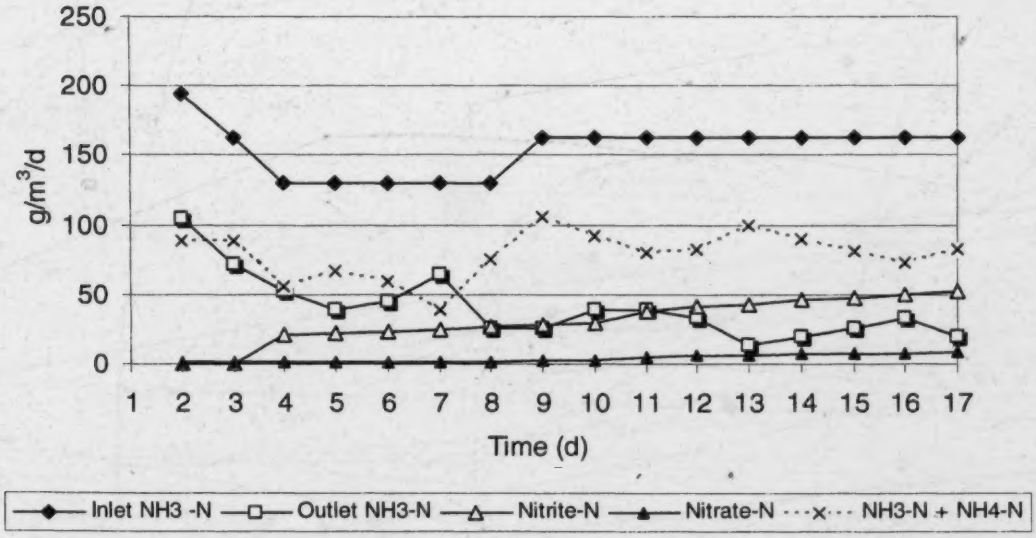


Figure F.6 Mass balance of nitrogen in the biofilter 2 trial 2 with 20 ppmv NH_3

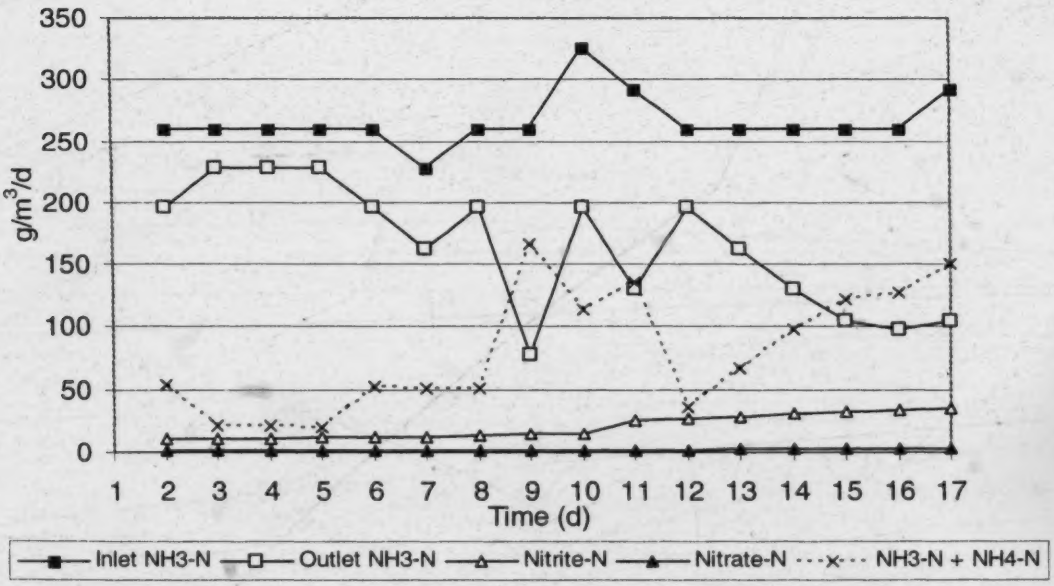


Figure F.7 Mass balance of nitrogen in the biofilter 3 trial 2 with 45 ppmv NH_3

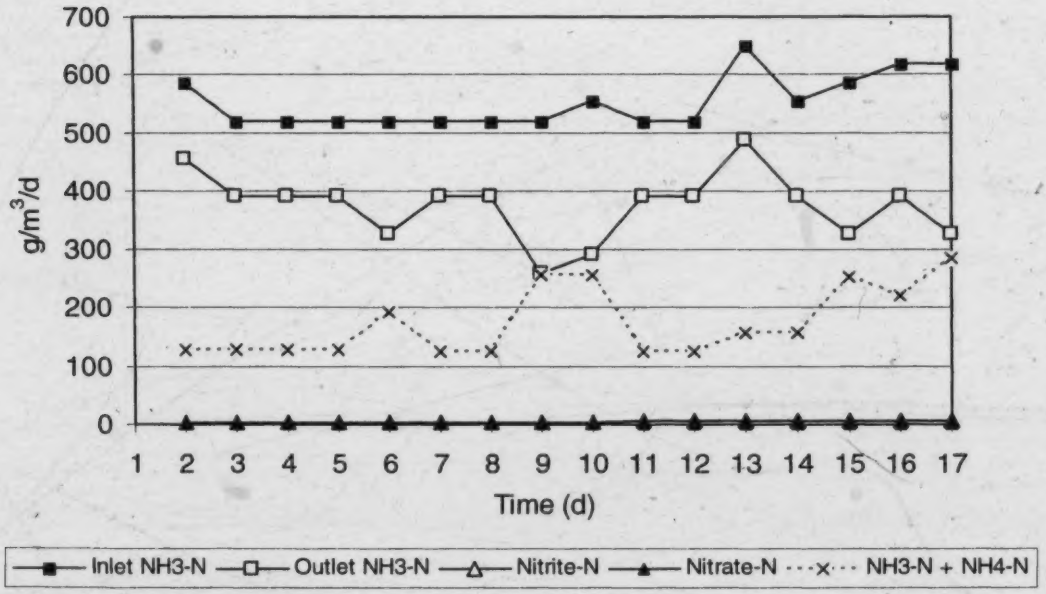


Figure F.8 Mass balance of nitrogen in the biofilter 4 trial 2 with 90 ppmv NH_3

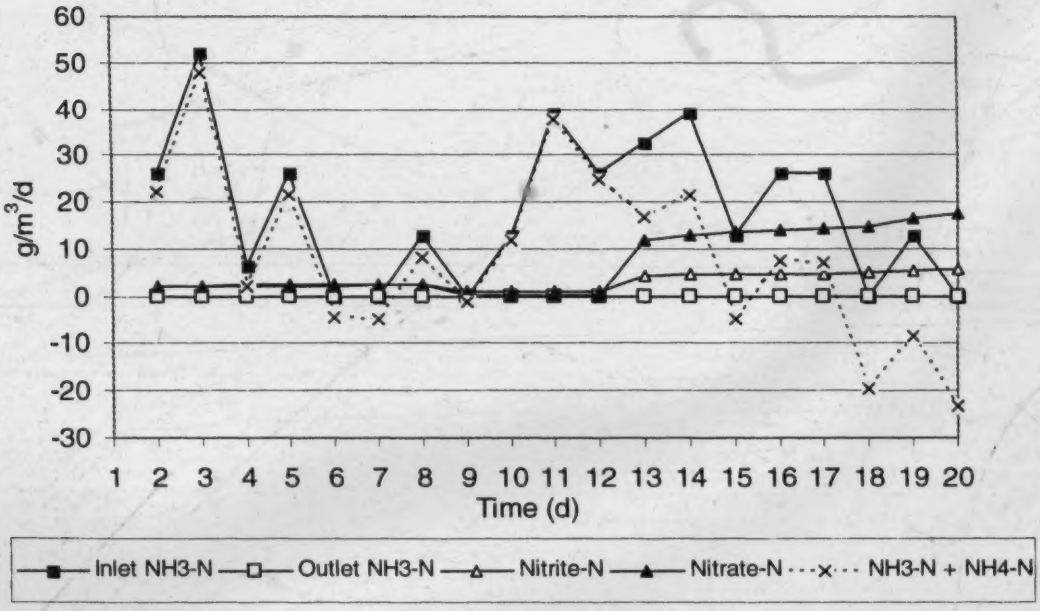


Figure F.9 Mass balance of nitrogen in the biofilter-1 trial 3 with no NH_3 injection

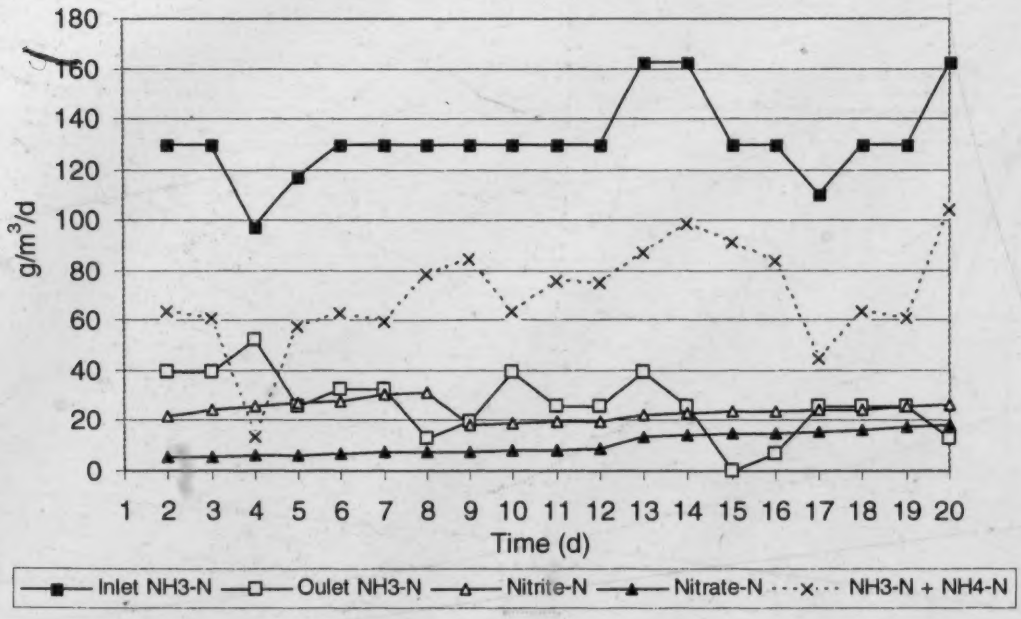


Figure F.10 Mass balance of nitrogen in the biofilter-2 trial 3 with 20 ppmv NH_3

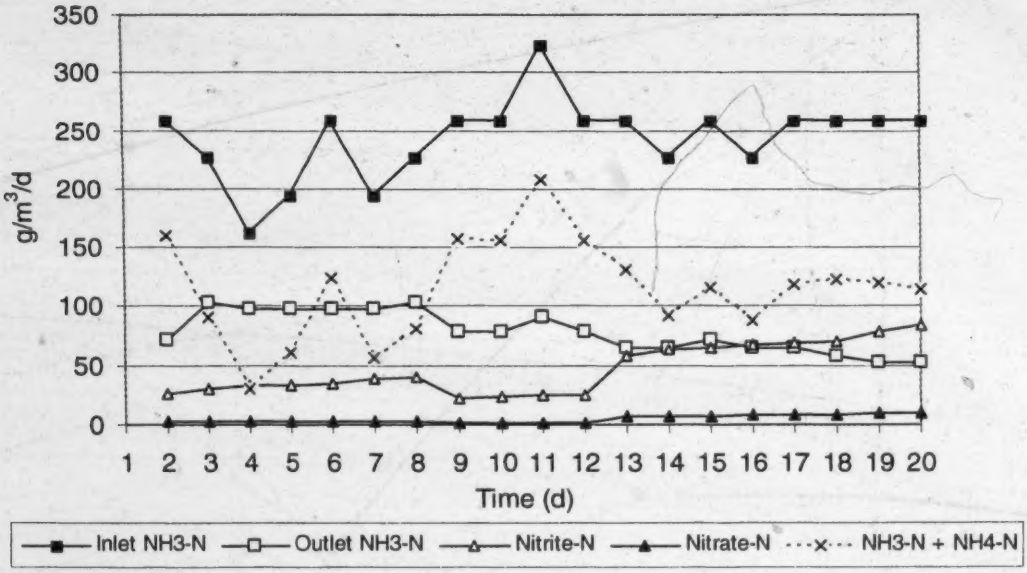


Figure F.11 Mass balance of nitrogen in the biofilter 3 trial 3 with 45 ppmv NH_3

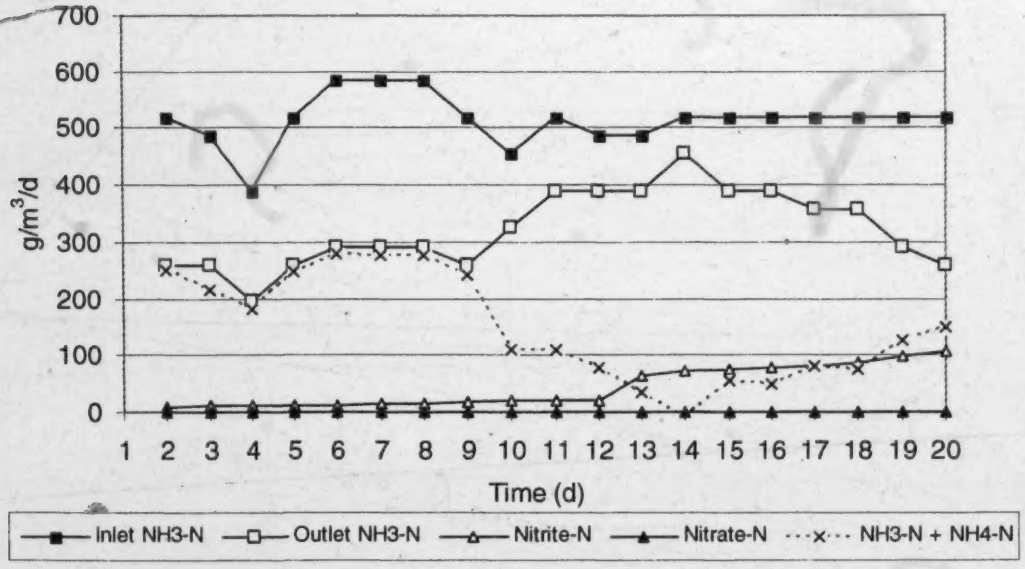


Figure F.12 Mass balance of nitrogen in the biofilter 4 trial 3 with 90 ppmv NH_3

Appendix G: Estimation of Water for Humidifying the Contaminated Air

In four steps the amount of water for any input data in the model will be predicted:

Step 1: With combination of numbers G-1, G-2 and G-3 of the following equations saturation vapor pressure (P_s) will be calculated.

Step 2: With using number G-4 equation the vapor pressure of the air at the inlet and outlet will be calculated.

Step 3: With combination of equations G-4, G-5, and G-6 we can figure out the humidity ratio (H) and air specific volume (Vsa).

Step 4: With combination of equations G-7, G-8 and G-9 the volume of water is needed will be predicted.

$$T = t + 273.15 \qquad \text{(G-1)}$$

Where:
t = Air temperature(°C)

T = Kelvin degree

$$273.16 \le T \le 533.16 \qquad \text{Ln}(P_s/R)=M=\frac{A+BT+CT^2+DT^3+ET^4}{FT-GT^2} \qquad \text{(G-2)}$$

$$Ps = R \times e^{M} \qquad \text{(G-3)}$$

ASAE Standards 1997 that Adapted from Keenan and Keyes (1936)

Where:
Ln = Natural logarithm (bace e), and e = 2.718

Ps = Saturation vapore at T, Pa

R = 22,105,649.25 $\qquad$ *D* = 0.12558×10^{-3}

A = 27,405.526 $\qquad$ *E* = -0.48502×10^{-7}

B = 97.5413 $\qquad$ *F* = 4.34903

C = -0.146244 $\qquad$ *G*=0.39381×10^{-2}

$$RH=P_v/P_s \qquad \text{(G-4)}$$

RH = Relative humidity

Pv = Vapor pressure, Pa

$$255.38 \le T \le 533.16 \qquad H = \frac{0.6219 P_v}{P_{atm} - P_v} \qquad \text{(G-5)}$$

$P_v < P_{atm}$

Where:
H = Humidity ratio (kg water/kg dry air)

$$255.38 \le T \le 533.16 \qquad V_{sa} = \frac{287T}{P_{atm} - P_v} \qquad \text{(G-6)}$$

$P_v < P_{atm}$

Vsa = Air specific volume (m^3/kg dry air)

$P_{atm} = 93{,}400$ (ASAE Standards 2003)

$$W_1 = \frac{q \times 3600 \times 24 \times H_1}{Vsa1 \times 1000} \qquad \text{(G-7)}$$

$$W_2 = \frac{q \times 3600 \times 24 \times H_2}{Vsa2 \times 1000} \qquad \text{(G-8)}$$

$$W = W_2 - W_1 \qquad \text{(G-9)}$$

Where:

W_1 = Volume of water available in the air at the inlet humidifier (m^3/d)

W_2 = Volume of water available in the air at the outlet of humidifier (m^3/d),

W = Volume of water used (m^3/d),

H_1 = Humidity ratio at the inlet (kg water/kg dry air),

H_2 = Humidity ratio at the outlet (kg water/kg dry air), and

q = Volume of air pass through humidifier per second (m^3/s)

Reference:

American Society of Agricultural Engineers (ASAE), 2003. ASAE STANDARDS 2003, 50 th Anniversary Edition. St. Joseph, MI: USA. Adupted and published by:ASAE.

Appendix H: Revised Predicting Model

```
10 ' Predicting model for design and performance of
biofilter based on inlet ammonia concentration
11 ON ERROR GOTO errorhandler
12 OPEN "u:\bhzuka~v\fqx7cc~3\summary.doc" FOR INPUT AS #1
13 CLOSE 1
14 OPEN "u:\bhzuka~v\fqx7cc~3\summary.doc" FOR APPEND AS #1
'12 OPEN "x:\xxxx\xxxx\summary.doc" FOR INPUT AS #1
'13 CLOSE 1
'14 OPEN "x:\xxxxx\xxxx\summary.doc" FOR APPEND AS #113
20 CLS : PRINT "hello - Predicting model for design and
performance of biofilter"
30 PRINT
40 PRINT
50 KEY OFF: WIDTH 80, 50: COLOR 7, 0: TRUE = 1: FALSE = 0
60 CLS : GOSUB 3530: PRINT : PRINT   'Header and
introduction
70 PRINT TAB(10); "    This biofiltration model predicts
design and       "
80 PRINT TAB(10); "operating parameters including: removal
efficiency    "
90 PRINT TAB(10); "(RE),elimination capacity (EC), volume of
media,      "
100 PRINT TAB(10); "empty bed retention time (EBRT), pH,
byproducts     "
110 PRINT TAB(10); "such as nitrite and nitrate, amount of
water needed   "
120 PRINT TAB(10); "for evaporation or increasing the
humidity of the     "
130 PRINT TAB(10); "polluted air, and amount of water for
conrolling the  "
140 PRINT TAB(10); "pH and toxicity of the byproducts. The
prediction of  "
150 PRINT TAB(10); "above parameters have conducted based on
availability "
160 PRINT TAB(10); "of the contaminated airflow, temperature
(inlet and   "
170 PRINT TAB(10); "outlet), ammonia and hydrogen sulfide
concentrations, "
180 PRINT TAB(10); "relative humidity (RH) at the inlet and
outlet, days  "
190 PRINT TAB(10); "of operation (14 days after starting the
opertation). "
200 PRINT TAB(10); "Finally, except overhead capital and
operation costs  "
```

```
210 PRINT TAB(10); "including power, water, and media
estimated."
220 LOCATE 22, 1: PRINT TAB(25); "Press any key to begin."
230 a$ = INKEY$: IF LEN(a$) = 0 THEN 230
240 ' Default values
250 qs = 20: t1 = 15: t2 = 15: c1 = 20: ss1 = .8: ss2 = 0:
rh1 = .5: rh2 = 1: d1 = 36: Ip = 2: vp = 120: timp = 24: np
= 1:
260 '
270 Iff = 2: vff = 120: timf = 24: nf = 1: pe = .11: pw =
.012: pm = 20
280 '
290 '
300 ' Entry point for changing data
310 '
320 CLS : GOSUB 3530: GOSUB 3590: 'Print header and input
screen
330 '
340 ' Interactively change values using a standard input
subroutine:
350 ' S6$ = default value  S1,S2=screen location   S3=1 is
numeric input
360 ' S4,S5=range          S9=length of input      S3=3 is
Y/N answer
370 ' S returns answer     S$ returns Y/N
380 '      In some cases, the default value is replaced with
an integer
390 '
400 'corresponding with a menu on line twenty three.
410 ' qs
420 S6$ = STR$(qs): S1 = 5: S2 = 60: S3 = 1: s4 = 0: S5 =
3000: S9 = 4: GOSUB 4020: qs = s
430 ' t1
440 S6$ = STR$(t1): S1 = 7: S2 = 60: S3 = 1: s4 = 0: S5 =
35: S9 = 4: GOSUB 4020: t1 = s
450    ' t2
460 S6$ = STR$(t2): S1 = 9: S2 = 60: S3 = 1: s4 = 0: S5 =
35: S9 = 4: GOSUB 4020: t2 = s
470 ' c1
480 S6$ = STR$(c1): S1 = 11: S2 = 60: S3 = 1: s4 = 0: S5 =
90: S9 = 4: GOSUB 4020: c1 = s
490  'ss1
500 S6$ = STR$(ss1): S1 = 13: S2 = 60: S3 = 1: s4 = 0: S5 =
1: S9 = 4: GOSUB 4020: ss1 = s
510   'ss2
520 S6$ = STR$(ss2): S1 = 15: S2 = 60: S3 = 1: s4 = 0: S5 =
1: S9 = 4: GOSUB 4020: ss2 = s
```

```
530  'rh1
540 S6$ = STR$(rh1): S1 = 17: S2 = 60: S3 = 1: s4 = 0: S5 =
100: S9 = 4: GOSUB 4020: rh1 = s
550   'rh2
560 S6$ = STR$(rh2): S1 = 19: S2 = 60: S3 = 1: s4 = 0: S5 =
100: S9 = 4: GOSUB 4020: rh2 = s
570   'd1
580 S6$ = STR$(d1): S1 = 21: S2 = 60: S3 = 1: s4 = 0: S5 =
360: S9 = 4: GOSUB 4020: d1 = s
590   'Ip
600 S6$ = STR$(Ip): S1 = 23: S2 = 60: S3 = 1: s4 = 0: S5 =
15: S9 = 4: GOSUB 4020: Ip = s
610   'vp
620 S6$ = STR$(vp): S1 = 25: S2 = 60: S3 = 1: s4 = 0: S5 =
220: S9 = 4: GOSUB 4020: vp = s
630   'timp
640 S6$ = STR$(timp): S1 = 27: S2 = 60: S3 = 1: s4 = 0: S5 =
24: S9 = 4: GOSUB 4020: timp = s
650   'np
660 S6$ = STR$(np): S1 = 29: S2 = 60: S3 = 1: s4 = 0: S5 =
10: S9 = 4: GOSUB 4020: np = s
670   'Iff
680 S6$ = STR$(Iff): S1 = 31: S2 = 60: S3 = 1: s4 = 0: S5 =
15: S9 = 4: GOSUB 4020: Iff = s
690   'vff
700 S6$ = STR$(vff): S1 = 33: S2 = 60: S3 = 1: s4 = 0: S5 =
220: S9 = 4: GOSUB 4020: vff = s
710   'timf
720 S6$ = STR$(timf): S1 = 35: S2 = 60: S3 = 1: s4 = 0: S5 =
24: S9 = 4: GOSUB 4020: timf = s
730   'nf
740 S6$ = STR$(nf): S1 = 37: S2 = 60: S3 = 1: s4 = 0: S5 =
20: S9 = 4: GOSUB 4020: nf = s
750   'pe
760 S6$ = STR$(pe): S1 = 39: S2 = 60: S3 = 1: s4 = 0: S5 =
.11: S9 = 4: GOSUB 4020: pe = s
770   'pw
780 S6$ = STR$(pw): S1 = 41: S2 = 60: S3 = 1: s4 = 0: S5 =
.11: S9 = 4: GOSUB 4020: pw = s
790   'pm
800 S6$ = STR$(pm): S1 = 43: S2 = 60: S3 = 1: s4 = 0: S5 =
40: S9 = 4: GOSUB 4020: pm = s
810
820 '                                    Check if values OK
830 COLOR 0, 7: LOCATE 4, 1: PRINT "CHANGE VALUES  (Y/N)?";
TAB(30); "N"
```

```
840 S6$ = "N": S1 = 4: S2 = 30: S3 = 3: S9 = 7: GOSUB 4020:
IF s$ = "Y" THEN 410
850 CLS : GOSUB 3530: LOCATE 12, 12: PRINT
860 '
'870 OPEN "output.txt" FOR OUTPUT AS #1
880 '
890 'Calculate temperature based on farenhite degree.
900 '
910 ' PRINT "the average temperature at the inlet and outlet
of the biofilters is used as the biofilter temperature (t)
but in this"
920 '
930 ' PRINT "this experiment there were not significant
differents between temperatures at the in let and outlets."
940 '
950 ' PRINT "tf1 and tf2 is used for quantitative
calculation of the amount of ammonia."
960 '
970 ' PRINT "t is used for calculation of the effect of the
temperature."
980 '
990  t = (t1 + t2) / 2
1000
1010 tf = (9 * t + 160) / 5
1020 '
1030 tf1 = (9 * t1 + 160) / 5
1040 tf2 = (9 * t2 + 160) / 5
1050 '
1060 'Calculate one pound mole of ammonia at tf1 and tf2
degree farenhite
1070 vt1 = 1 * .73 * (460 + tf1)
1080 vt2 = 1 * .73 * (460 + tf2)
1090 PRINT "One pound mole of ammonia at tf1 degree (F)";
TAB(50); USING "###.#"; vt1; : PRINT TAB(56); "Ib-mol"
1100 PRINT
1110 PRINT "one pound mole of ammonia at tf2 degree (F)";
TAB(50); USING "###.#"; vt2; : PRINT TAB(56); "Ib-mol"
1120 PRINT
1130 'Calculate the effect of temperature
1140 'PRINT "a is the effect of the temperature on the
microbial activity"
1150 e = 2.718
1160 a = e ^ (.098 * (t - 15))
1170 GOTO 3830: 'OUTPUT
1180 '
1190 '
```

```
1200 'cgi is the mass of ammonia goes to the pilot scale
biofilters per day.
1210 'cgo is the mass of ammonia goes out of the pilot scale
biofilter.
1220 'EC is the elimination capacity of the pilot scale
biofilters (normalized factor of volume airflow and time
normally explain as g/m3/h.
1230 'ECt is the elimination capacity normalized with the
effect of temperature.
1240 'In this predictive model the unit of EC is g/m3/d.
1250 'q1 is the volume of air pass through the pilot scale
biofilters per day (L/d).
1260 'vf is the volume of the pilot sacale biofilter m3.
1270 'Empty bed retention time (EBRT) for the pilot sacle
biofilters.
1280 'EBRT1 is predicted retention time for treating the
available contaminated air based on eliminating ammonia to
zero ppm.
1290 'Removal efficiency (RE)of ammonia in the pilot scale.
1295 'Concentration of ammonia at the outlet (c2) ppm.
1300 'vfs is the volume of the material (expanded
polystyrene) in the bioscrubber m3
1310 'Total average of the retention time in the pilot
scale=(vf*1000)/q+(vfs*1000)/(4*q)=(150/19)+(325/(4*19)=12.1
6 second.
1320 'V1 is the predicted volume of the course compost over
1 inches size needed for treating Qs liters polluted air
(m3).
1330 'cgit is the mass of ammonia for treating per day
available in the source malodourous air.
1340 'cgot is the mass of ammonia that should go out from
the biofilter with 10 second retention time.
1350 q = 19
1360 q1 = 86400 * q
1370 'PRINT "EC = ((c1-c2)*q1)/Vf=(cgi-cgo)/vf"
1380 '
1390 '
1400 IF ss1 > 1 THEN END
1410 'pridiction of biofilter parameters such as  cgi, cgo,
EC, pH, EBRT, RE
1415 'under the pilot scale conditionsc1=5 to 90 ppmv
average temperature 15 celsious.
1420 'Calculations:
1430 ' Volume of scrubber material = .325 m3
1440 ' Volume of biofilter material=.15 m3
1450 RE = (.0047 * (c1 ^ 2) - 1.04 * c1 + 99.24)
1455 c2 = (100 - RE) * c1 / 100
```

```
1460 IF ss1 <= 1 AND c1 <= 90 THEN cgi = (q1 * 17 * 453 *
c1) / (28.3 * 378.87 * 1000000)
1470 cgo = (q1 * 17 * 453 * c2) / (28.3 * 378.87 * 1000000)
1480 EC = ((cgi - cgo) / .15)
1490 ect = ((cgi - cgo) / .15) * a
1500 IF ss1 <= 1 AND c1 <= 90 THEN vf = cgi / ect
1510 IF c1 >= 0 AND c1 <= 90 THEN pH = -(.0002 * c1 ^ 2) +
.0262 * c1 + 7.4576
1520 'calculation of empty bed retention time (EBRT)
1530 'Retention time of scrubber=0.325*1000/80= 4s
1540 EBRT = (.15 * 1000) / q
1550 '
1555 '
1560 IF ss1 <= 1 AND c1 <= 90 THEN cgit = (qs * 86400 * 17 *
453 * c1) / (28.3 * vt1 * 1000000)
1565 'PRINT c1; ss1; qs; vt1; cgit: END
1570 cgot = (qs * 86400 * 17 * 453 * c2) / (28.3 * vt2 *
1000000)
     'Assumption 5<C1<20 ppm
1580 v1 = (cgit / ect)
1590 ebrt1 = v1 * 1000 / qs
1600 PRINT "Mass of ammonia (in) pilot scale (cgi)",
TAB(50); USING "###.#"; cgi; : PRINT TAB(56); "(g/d)"
1610 PRINT
1620 PRINT "Mass of ammonia (out) pilot scale (cgo)",
TAB(50); USING "###.#"; cgo; : PRINT TAB(56); "(g/d)"
1630 PRINT
1640 PRINT "Elimination capacity (EC) pilot scale", TAB(50);
USING "###.#"; EC; : PRINT TAB(56); "(g/m3/d)"
1650 PRINT
1660 PRINT "Elimination capacity with effect of temp (ECt)";
TAB(50); USING "###.#"; ect; : PRINT TAB(56); "(g/m3/d)"
1670 PRINT
1680 PRINT "predicted pH value in pilot scale", TAB(50);
USING "###.#"; pH
1690 PRINT
1700 PRINT "Empty bed retention time (EBRT) pilot", TAB(50);
USING "###.#"; EBRT; : PRINT TAB(56); "s"
1710 PRINT
1720 PRINT "Predicted retention time minimum (EBRT1)",
TAB(50); USING "###.#"; ebrt1; : PRINT TAB(56); "s"
1730 PRINT
1740 PRINT "Removal efficiency (RE) pilot scale", TAB(50);
USING "###.#"; RE; : PRINT TAB(56); "%"
1745 PRINT
1750 PRINT "NH3 at the outlet of  pilot scale (c2)",
TAB(50); USING "###.#"; c2; : PRINT TAB(56); "ppm"
```

```
1755 PRINT
1760 PRINT "Mass of ammonia available in the polluted gas";
TAB(49); USING "####.#"; cgit; : PRINT TAB(56); "(g/d)"
1770 PRINT
1780 PRINT "Predicted volume of media based on ECt",
TAB(50); USING "###.#"; v1; : PRINT TAB(56); "m3"
1790 '
1820 '
1825 IF c1 >= 90 THEN PRINT "NH3 overlimit!!!!!": END
1830 x1 = c1
1840 IF x1 > 0 AND x1 < 90 THEN y1 = 6.13 * x1 + 15.6
1850 y2 = (.027 * (x1 ^ 2) + 1.35 * x1 - 1.91)
1860 y3 = (.013 * (x1 ^ 2) + 1.482 * x1 -1.41)
1870 y4 = NO3 - N: y6 = NO3 - N1
1880 IF x1 <= 20 AND x1 >= 0 THEN y4 = (.2543 * x1 + 4.17)
1890 IF x1 > 20 AND x1 <= 90 THEN y6 = .0039 * (x1 ^ 2) -
.5675 * x1 + 19.933
1900 y5 = (y1 - y2 - y3 - y4)
1910 '
'1920 PRINT #1, "Amount of ammonia gas inter to the
biofilter,", cgi, ",g/m3/d"
1921 PRINT
1930 PRINT "Temperature effect", TAB(50); USING "###.#"; a
'To Screen
'1935 PRINT #1, "Temperature effect", TAB(50); USING
"###.#"; a 'To File
1940 PRINT
1950 PRINT "NH3-N in pilot scale", TAB(50); USING "###.#";
y1; : PRINT TAB(56); "g/m3/d"
1960 PRINT
1970 PRINT "NH3-N out pilot scale", TAB(50); USING "###.#";
y2; : PRINT TAB(56); "g/m3/d"
1980 PRINT
1990 PRINT "Nitrite-N pilot scale", TAB(50); USING "###.#";
y3; : PRINT TAB(56); "g/m3/d"
2000 PRINT
2010 PRINT "Nitrate-N pilot scale", TAB(50); USING "###.#";
y4; : PRINT TAB(56); "g/m3/d"
2020 PRINT
2030 PRINT "Total NH3-N and NH4-N pilot scale", TAB(50);
USING "###.#"; y5; : PRINT TAB(56); "g/m3/d"
2040 PRINT
2060 'PRINT "Nitrate-N1", : PRINT y6, : PRINT "g/m3/d"
     'Assumption all NH3-N eliminate to nitrite and nitrate
and the maximum rate of measured 45.5 g/m3/d for 20 ppm
ammonia concentrations.
     v2 = cgit / ((y3 + y4) * a)
```

```
     ebrt2 = (v2 * 1000) / qs
     IF ebrt2 < 20 THEN
       v2 = (qs / 1000) * 20
       ebrt2 = 20
     END IF
     PRINT "Volume based on NO2-N and NO3-N (V2)", TAB(50);
USING "###.##"; v2; : PRINT TAB(56); "m3"
     PRINT
     PRINT "EBRT2 based on NO2-N and NO3-N", TAB(50); USING
"###.#"; ebrt2; : PRINT TAB(56); "s"
     PRINT
     v3 = cgit / (42 * a)
     ebrt3 = (v3 * 1000) / qs
     IF ebrt3 < 20 THEN
       v3 = (qs / 1000) * 20
       ebrt3 = 20
     END IF

     PRINT "Volume based on maximum nitrification", TAB(50);
USING "###.##"; v3; : PRINT TAB(56); "m3"
     PRINT
     PRINT "EBRT3 based on maximum nitrification", TAB(50);
USING "###.#"; ebrt3; : PRINT TAB(56); "s"
2070
2080 PRINT : PRINT "Press key to proceed"; : INPUT x: CLS
2090 '
2095      'wa=Minimum range of water is needed for washing
out the chemicals (m3/m3/d))
2096     'wa1=Maximum range of water is needed for flushing
out the chemicals (m3)
2100 IF d1 <= 36 THEN
     wa = (v2 * ((.2578 * c1) + 12.884)) / 1000: wa1 = 0
     ELSEIF d1 > 36 THEN
     wa1 = (v2 * ((1.3944 * c1) + 15.311)) / 1000: wa = 0
     END IF

2110 'Calculation of amount of water needed for humidifier
2120 R = 22105649.25#: A1 = -27405.526#: B = 97.5413: ca = -
.146244: d = .12558 * 10 ^ -3: E1 = -.48502 * 10 ^ -7
2130 F = 4.34903: G = .39381 * 10 ^ -2
2140 'Changing temperature to Kelvin
2150 't1 temperature inlet t2 temperature outlet
2160 Tk = t1 + 273.15
2170 M1 = (A1 + B * Tk + ca * Tk ^ 2 + d * Tk ^ 3 + E1 * Tk
^ 4) / (F * Tk - G * Tk ^ 2)
2180 IF Tk >= 273.16 AND Tk <= 533.16 THEN Ps1 = R * e ^ M1
2190 Pv1 = Ps1 * rh1
```

```
2200 IF Pv1 <= 93400 THEN Vsa1 = 287 * Tk / (93400 - Pv1)
2210 H1 = .6219 * Pv1 / (93400 - Pv1)
2220
2230 'Pv or Vaper pressure(pascal)
2240
2250 'H Humidity ratio kg water/kg dry air
2260 '
2270 Tk2 = t2 + 273.15
2280 M2 = (A1 + B * Tk2 + ca * Tk2 ^ 2 + d * Tk2 ^ 3 + E1 *
Tk2 ^ 4) / (F * Tk2 - G * Tk2 ^ 2)
2290 IF Tk2 >= 273.16 AND Tk2 <= 533 THEN Ps2 = R * e ^ M2
2300 Pv2 = Ps2 * rh2
2310 IF Pv2 < 93400 THEN Vsa2 = 287 * Tk2 / (93400 - Pv2)
2320 H2 = .6219 * Pv2 / (93400 - Pv2)
2330
2340 'Amount of water=W1-W2 Density of water=1000Kg/m3
2350 Qs1 = qs / 1000
2360 W1 = Qs1 * 3600 * 24 * H1 / (Vsa1 * 1000)
2370 W2 = Qs1 * 3600 * 24 * H2 / (Vsa2 * 1000)
2380 W = W2 - W1
2390 'PRINT "Specific volume of inlet air", : PRINT Vsa1, :
PRINT "m3/kg dry air"
2400 'PRINT "Specific volume of outlet air", : PRINT Vsa2, :
PRINT "m3/kg dry air"
2410 'PRINT "Humidity ratio of inlet air", : PRINT H1, :
PRINT "kg water/ kg dry air"
2420 'PRINT "Humidity ratio of outlet air", : PRINT H2, :
PRINT "kg water/ kg dry air"
2430 PRINT "Amount of water available in the inlet air per
day", : PRINT W1, : PRINT "m3/day"
2440 PRINT "Amount of water available in the outlet air per
day", : PRINT W2, : PRINT "m3/day"
2450 PRINT "Amount of water needed for humidifier per day",
: PRINT W, : PRINT "m3/d"
2455 PRINT "Minimum water for flushing chemicals (d1<=36)",
: PRINT wa, : PRINT "m3/d"
2457 PRINT "Maximum water for flushing chemicals (d1>=36)",
: PRINT wa1, : PRINT "m3/d"
2460 'estimation of Nitrite Concentration
2470
2480 'N1=Nitrite concentration at average 15 Celsius degree
and average 2 ppmv ammonia
2490 'N2=Nitrite concentration at average 15 Celsius degree
and average 21 ppmv ammonia
2500 'N3=Nitrite concentration at average 15 Celsius degree
and average 45 ppmv ammonia
```

```
2510 'N4=Nitrite concentration at average 15 Celsius degree
and average 87 ppmv ammonia
2520
2530 N1 = (.126 * d1 ^ 2 - .155 * d1 + 156)
2540 PRINT
2550 N2 = (-6.71 * d1 ^ 2 + 335.94 * d1 + 384.56)
2560 PRINT

2570 N3 = (141.6 * d1 + 289.02)
2580 PRINT
2590 N4 = (4.8671 * d1 ^ 2 - 26.81 * d1 + 499.93)
2600
2610 PRINT "NO2 with 2 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; N1; : PRINT TAB(57); "ppm"
2620 PRINT "NO2 with 21 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; N2: : PRINT TAB(57); "ppm"
2630 PRINT "NO2 with 45 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; N3: : PRINT TAB(57); "ppm"
2640 PRINT "NO2 with 87 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; N4: : PRINT TAB(57); "ppm"
2650 c3 = 2
2660 c4 = 21
2670 c5 = 45
2680 c6 = 87
2690 'ma=slope of the line
2700 ma = (N2 - N1) / (c4 - c3)
2710 IF c1 >= 2.08 AND c1 <= 21.35 THEN
2720   ya = N1 + ma * (c1 - c3): yb = 0: yc = 0
2730   mb = (N3 - N2) / (c5 - c4)
2740 ELSEIF c1 > 21.35 AND c1 <= 45.08 THEN
2750   yb = N2 + mb * (c1 - c4): ya = 0: yc = 0
2760   MC = (N4 - N3) / (c6 - c5)
2770 ELSEIF c1 > 45.08 AND c1 <= 87.25 THEN
2775   yc = N3 + MC * (c1 - c5): ya = 0: yb = 0
2776 END IF
2780 IF c1 > 87.25 THEN GOTO 2060
2790
2800 PRINT "predicted NO2 with c1 ppm NH3 at day:", TAB(38);
: PRINT d1
2810 PRINT ; USING "####.#"; ya; : PRINT TAB(15); "ppm"
2820 PRINT ; USING "####.#"; yb; : PRINT TAB(15); "ppm"
2830 PRINT ; USING "####.#"; yc; : PRINT TAB(15); "ppm"
2840 PRINT
2850 'estimation of Nitrate Concentration
2860 'O1=Nitrate concentration at average 15 Celsius degree
and average 2 ppmv ammonia
```

```
2870 'O2=Nitrate concentration at average 15 Celsius degree
and average 21 ppmv ammonia
2880 'O3=Nitrate concentration at average 15 Celsius degree
and average 45 ppmv ammonia
2890 'O4=Nitrate concentration at average 15 Celsius degree
and average 87 ppmv ammonia
2900
2910 O1 = (.049 * d1 ^ 2 - 12.95 * d1 + 311.02)
2920 PRINT
2930 O2 = (2.[illegible]6 * d1 ^ 2 - 17.733 * d1 + 272.22)
2940 PRINT
2950 O3 = (.362 * d1 ^ 2 - 1.5392 * x + 71.567)
2960 PRINT
2970 O4 = (.247 * d1 ^ 2 - 8.7103 * d1 + 122.69)
2980
2990 PRINT "NO3 with 2 ppm NH3 pilot at day 36 ", TAB(48);
USING "####.#"; O1; : PRINT TAB(57); "ppm"
3000 PRINT "NO3 with 21 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; O2; : PRINT TAB(57); "ppm"
3010 PRINT "NO3 with 45 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; O3; : PRINT TAB(57); "ppm"
3020 PRINT "NO3 with 87 ppm NH3 pilot at day 36", TAB(48);
USING "####.#"; O4; : PRINT TAB(57); "ppm"
3030 'md=slope of the line
3040 md = (O2 - O1) / (c4 - c3)
3050 IF c1 >= 2.08 AND c1 <= 21.35 THEN
3055 yd = O1 + md * (c1 - c3): ye = 0: yf = 0
3060
3070 me = (O3 - O2) / (c5 - c4)
3080 ELSEIF c1 > 21.35 AND c1 <= 45.08 THEN
3085 ye = O2 + me * (c1 - c4): yd = 0: yf = 0
3090
3100 mf = (O4 - O3) / (c6 - c5)
3120 ELSEIF c1 > 45.08 AND c1 <= 87.25 THEN
3125 yf = O3 + mf * (c1 - c5): yd = 0: ye = 0
3126 END IF
3130 IF c1 > 87.25 THEN GOTO 2060
3140
3150 PRINT "predicted NO3 with c1 ppm NH3 at day:", TAB(38);
: PRINT d1
3160 PRINT ; USING "####.#"; yd; : PRINT TAB(15); "ppm"
3170 PRINT ; USING "####.#"; ye; : PRINT TAB(15); "ppm"
3180 PRINT ; USING "####.#"; yf; : PRINT TAB(15); "ppm"
3190 'stimation of biofilter cost (Assumption all pumps and
fans are the same)
3200 '1- Capital Cost
3210 Tcm = v2 * pm
```

```
3220
3230 PRINT ; "Cost of coarse compost media", TAB(48); USING
"####.##"; Tcm; : PRINT TAB(57); "CN$"
3240 '2- Operating Cost
3250
3260 '2-1 Cost of electricity
3270 'power(watt)=V*I
3280 'Ip=Amper of the pump
3290 'vp=voltage of the pump Power = Po = Vp * Ip(watt)
3300 'Timp=Hours that pumps are working per day
3310 'np=number of pumps are working
3320 'Iff=Amper of fans
3330 'vff=voltage of the fan
3340 'Timf=Hours that fans are working per day
3350 'nf=number of fans are working per day
3360 'pe=price of electricity per kwh
3370 'pw=price of water per m3
3380 'pm=price of media per m3
3390 'TEP=Total electricity price per day (Canadian dollars)
3400 '
3410 TEP = (vp * Ip * timp * np + Iff * vff * timf * nf) *
pe / 1000
3420
3430 PRINT ; "The cost of electricity per day", TAB(49);
USING "###.##"; TEP; : PRINT TAB(57); "CN$"
3440 '2-2 Cost of water
3450 'Price of water=1.2 cents/gal Gallon (Canadian)=4.54
Liter
3460 Tpw = (1000 * (W + wa + wa1) / (4.54)) * pw
3470 PRINT "The cost of water per day", TAB(49); USING
"###.##"; Tpw; : PRINT TAB(57); "CN$"
3471 PRINT #1, USING "###.#"; t1; c1; a;
3472 PRINT #1, USING "######.#"; cgit;
3473 PRINT #1, USING "#####.#"; ect; y3; y4; v2; ebrt2; v3;
ebrt3
3480
3490 PRINT : PRINT TAB(15); : PRINT "Press 1 to quit; 2 to
change values"; : INPUT x
3500 IF x = 1 THEN CLOSE : END
3510 CLS
3520 GOTO 300 'End of program.  Go back to beginning to
start another iteration.
3530 '
3540 ' Clear screen and Print Header
3550 '
3560 CLS : COLOR 0, 7: PRINT TAB(17); "A BIOFILTRATION MODEL
FOR AGRICULTURE FACILITIES"; ""
```

```
3570 PRINT TAB(17); "                                    ": COLOR
7, 0: PRINT
3580 RETURN
3590 '
3600 ' Print screen of input data
3610 '
3620 PRINT : PRINT TAB(10); "Available polluted airflow
(L/s)"; TAB(60); qs
3630 PRINT : PRINT TAB(10); "Temperature at the inlet of
biofilter (C)"; TAB(60); t1
3640 PRINT : PRINT TAB(10); "Temperature at the outlet of
biofilter (C)"; TAB(60); t2
3650 PRINT : PRINT TAB(10); "Ammonia concentration of the
polluted air (ppm)"; TAB(60); c1
3660 PRINT : PRINT TAB(10); "Hydrogen sulfide concentration
at the inlet "; TAB(60); ss1
3670 PRINT : PRINT TAB(10); "Hydrogen sulfide concentration
at the outlet"; TAB(60); ss2
3680 PRINT : PRINT TAB(10); "Relative humidity of air at the
inlet (%)"; TAB(60); rh1
3690 PRINT : PRINT TAB(10); "Relative humidity of air at the
outlet (%)"; TAB(60); rh2
3700 PRINT : PRINT TAB(10); "Days of operating after 14 days
of starting"; TAB(60); d1
3710 PRINT : PRINT TAB(10); "Amper of the pump"; TAB(60); Ip
3720 PRINT : PRINT TAB(10); "Voltage used for the pump";
TAB(60); vp
3730 PRINT : PRINT TAB(10); "Time that pumps are working (h)
per day"; TAB(60); timp
3740 PRINT : PRINT TAB(10); "Number of pumps are working per
day"; TAB(60); np
3750 PRINT : PRINT TAB(10); "Amper of one of the fans";
TAB(60); Iff
3760 PRINT : PRINT TAB(10); "Voltage of one of the fans";
TAB(60); vff
3770 PRINT : PRINT TAB(10); "Time that fans are working
(h)"; TAB(60); timf
3780 PRINT : PRINT TAB(10); "Number of fans are working per
day"; TAB(60); nf
3790 PRINT : PRINT TAB(10); "Price of electricity/kwh";
TAB(60); pe
3800 PRINT : PRINT TAB(10); "Price of water (CN $/ galon)";
TAB(60); pw
3810 PRINT : PRINT TAB(10); "Price of media per m3";
TAB(60); pm
3820 RETURN
3830 '
```

```
3840 ' Output
3850 '
3860 CLS : GOSUB 3530: GOSUB 1200 ' Print page one
3870 LOCATE 4, 1: COLOR 0, 7: PRINT "Press any key to see
more OUTPUT"
3880 COLOR 7, 0: a$ = INKEY$: IF LEN(a$) = 0 THEN 3880
3890 'CLS : GOSUB 3140    ' Print page two of initial output
3900 'LOCATE 23, 1: COLOR 0, 7: PRINT "Press any key to see
more OUTPUT"
3910 'COLOR 7, 0: a$ = INKEY$: IF LEN(a$) = 0 THEN 3910
3920 'CLS : GOSUB 3530    'Print energy partition
3930 'LOCATE 23, 1: COLOR 0, 7: PRINT "Press any key to see
more OUTPUT"
3940 'COLOR 7, 0: a$ = INKEY$: IF LEN(a$) = 0 THEN 3940
3950 'CLS : GOSUB 3770
3960 '   CHANCE TO RERUN OR end
3970 COLOR 0, 7: LOCATE 23, 1: PRINT "CHANGE INPUT VALUES
(Y/N)?"; TAB(30); "Y"
3980 S6$ = "Y": S1 = 23: S2 = 30: S3 = 3: S9 = 7: GOSUB
4020: IF s$ = "Y" THEN 1820
3990 CLS : CLEAR : CLOSE #1
4000 END
4010
4020 ' INPUT SUBROUTINE
4030 '
4040 '    S1,S2=POSITION  S3: 1=Numeric 2=String 3=Y/N
S6$,S$=IN,OUT
4050 '    S4,S5 = Range   S9 = Length
4060 s$ = ""
4070 GOSUB 4190: PRINT SPC(LEN(s$));
4080 S8 = FALSE: GOSUB 4190: GOSUB 4200: GOSUB 4220: GOSUB
4380
4090 IF s$ = "" THEN s$ = S6$: GOTO 4110
4100 IF S3 = 1 THEN GOSUB 4400: IF S8 = TRUE THEN 4070
4110 IF S3 = 1 THEN GOSUB 4520: IF S8 = TRUE THEN 4070
4120 IF S3 = 3 THEN GOSUB 4570: IF S8 = TRUE THEN 4070
4130 IF S3 = 1 THEN s = VAL(s$)
4140 'COLOR 7, 0
4141 LOCATE 46, 1, 0
4142 PRINT TAB(80);
4143 LOCATE , , 1
4150 DEF SEG = 0: POKE 1050, PEEK(1052): DEF SEG : POKE 106,
0'Clear buffers
4160 RETURN
4170 '
4180 LOCATE S1, S2, 1: RETURN          'POSITION CURSOR
VISIBLE
```

```
4190 LOCATE S1, S2, 0: RETURN          'POSITION CURSOR
INVISIBLE
4200 PRINT S6$; : GOSUB 4180: RETURN 'PRINT DEFAULT
4210 '
4220 s$ = ""                           'TRANSPARENT CURSOR
ROUTINE
4230 S1$ = INPUT$(1)
4240 s = ASC(S1$): IF s <> 13 GOTO 4280
4250 IF s$ = "" THEN GOSUB 4190: GOSUB 4200: RETURN
4260 IF LEN(s$) < LEN(S6$) THEN PRINT SPC(LEN(S6$) -
LEN(s$));
4270 RETURN
4280 IF s < 32 GOTO 4340
4290 IF s = 34 THEN S1$ = "'"
4300 s$ = s$ + S1$
4310 PRINT S1$; : IF S9 > 0 AND LEN(s$) > S9 THEN 4350
4320 IF LEN(s$) = 1 THEN GOSUB 4190: PRINT SPC(S9); : GOSUB
4180: PRINT s$;
4330 GOTO 4230
4340 IF LEN(s$) < 1 GOTO 4220
4350 IF LEN(s$) = 1 THEN PRINT CHR$(29); " "; CHR$(29); :
GOTO 4220
4360 s$ = LEFT$(s$, LEN(s$) - 1): PRINT CHR$(29); " ";
CHR$(29); : GOTO 4230
4370 '
4380 IF s$ = "<" THEN CLS : PRINT "NORMAL EXIT"; : CLS :
LOCATE , , 1: END ELSE RETURN
4390 '
4400 S1$ = s$: S7 = 0                                  'CHECK
FOR NUMERIC INPUT
4410 IF LEFT$(S1$, 1) = " " THEN S1$ = RIGHT$(S1$, LEN(S1$)
- 1): GOTO 4410
4420 IF RIGHT$(S1$, 1) = " " THEN S1$ = LEFT$(S1$, LEN(S1$)
- 1): GOTO 4420
4430 IF LEN(S1$) < 1 GOTO 4480
4440 FOR s = 1 TO LEN(S1$): S6 = ASC(MID$(S1$, s, 1))
4450 IF S6 >= 48 AND S6 <= 57 GOTO 4490
4460 IF (S6 = 43 OR S6 = 45) AND s = 1 THEN 4490
4470 IF S6 = 46 AND S7 = 0 THEN S7 = 1: GOTO 4490
4480 S2$ = "PLEASE ENTER NUMBERS ONLY": S1$ = "": GOSUB
4620: RETURN
4490 NEXT
4500 RETURN
4510 '
4520 S6 = VAL(s$)       'CHECK FOR PROPER LIMITS
4530 IF S6 < s4 THEN S2$ = "INPUT BELOW": S1$ = STR$(s4):
GOSUB 4620: GOTO 4550
```

```
4540 IF S6 > S5 THEN S2$ = "INPUT ABOVE": S1$ = STR$(S5):
GOSUB 4620
4550 RETURN
4560 '
4570 IF LEFT$(s$, 1) = "y" OR LEFT$(s$, 1) = "Y" THEN s$ =
"Y": GOTO 4600'Y/N ?
4580 IF LEFT$(s$, 1) = "n" OR LEFT$(s$, 1) = "N" THEN s$ =
"N": GOTO 4600
4590 S2$ = "PLEASE ANSWER EITHER YES OR NO": S1$ = "": GOSUB
4620
4600 RETURN
4610 '
4620 COLOR 31, 0, 0: BEEP: LOCATE 46, 1, 0'ERROR FOR ALL
CONDITIONS
4630 PRINT "     "; S2$; S1$; TAB(80); 'PRINT ERROR
4640 COLOR 7, 0, 0: S8 = TRUE
4650 RETURN


errorhandler:
IF ERR = 53 THEN
  OPEN "u:\bhzuka~v\fqx7cc~3\summary.doc" FOR APPEND AS #1
  PRINT #1, TAB(4); "c1= the ammonia concentration (ppm)"
  PRINT
  PRINT #1, TAB(4); "a= the effect of temperature"
  PRINT
  PRINT #1, TAB(4); "cgit= the amount of NH3-N that is
available (g/d)"
  PRINT
  PRINT #1, TAB(4); "ect= the elimination capacity with the
effect of temperature (g/m3/d)"
  PRINT
  PRINT #1, TAB(4); "y3= the prediction of Nitrite nitrogen
(g/m3/d)"
  PRINT
  PRINT #1, TAB(4); "y4= the prediction of Nitrate nitrogen
(g/m3/d)"
  PRINT
  PRINT #1, TAB(4); "v1= the prediction of the volume of the
media based on EC (m3)"
  PRINT
  PRINT #1, TAB(4); "ebrt1= the prediction of the empty bed
retention time based on EC (s)"
  PRINT
  PRINT #1, TAB(4); "v2= the prediction of the volume of the
media based on NO2-N and NO3-N (m3)"
  PRINT
```

```
  PRINT #1, TAB(4); "ebrt2= the prediction of the EBRT based
on NO2-N and NO3-N (s)"
  PRINT
  PRINT #1, TAB(4); "t1"; TAB(8); "c1"; TAB(14); "a";
TAB(20); "cgit"; TAB(27); "ect"; TAB(35); "y3"; TAB(42);
"y4"; TAB(49); "v2"; TAB(54); "ebrt2"; TAB(63); "v3";
TAB(68); "ebrt3"
  GOTO 20
ELSE
  PRINT ERR
  END
END IF
END
```

Testing the Model:

In the following the model tested under different conditions of inputs including temperature, ammonia concentrations however, tables H-1, H-2, H-3, H-4 show the outputs of the model. The EBRT limited in the model higher than 20s due to the diffusion of ammonia to the biofilm because with injection of 20 ppm ammonia with 10s EBRT 75% of the ammonia absorbed by the biofilter on the overall average.

Where:

t1= the temperature of the contaminated air (°C)

c1= the ammonia concentration (ppm)

a= the effect of temperature

cgit= the amount of NH3-N that is available (g/d)

ect= the elimination capacity with the effect of temperature ($g/m^3/d$)

y3=the prediction of Nitrite nitrogen under experiment conditions ($g/m^3/d$)

y4= the prediction of Nitrate nitrogen under experiment conditions ($g/m^3/d$)

V2= the prediction of the volume of the media based on NO2-N and NO3-N (m^3)

EBRT2= the prediction of the EBRT based on NO2-N and NO3-N (s)

V3= the prediction of volume of media based on maximumnitrification rate (m^3)

EBRT3= the prediction of EBRT based on maximum nitrification rate (s)

Appendix H.1 Prediction of volume of media and EBRT based on two conditions (production of nitrite and nitrate under experiment condition and maximum nitrification rate) with the effect of temperature for airflow (qs)2000 L/s, temperature (t1)10 to 25 °C, ammonia concentrations (c1) 20 ppmv

t1	c1	a	cgit	ect	y3	y4	v2	EBRT2	V3	EBRT3
10.0	20.0	0.6	2526.0	128.5	36.2	9.3	90.6	45.3	98.2	49.1
11.0	20.0	0.7	2517.2	128.0	36.2	9.3	81.9	40.9	88.7	44.3
12.0	20.0	0.7	2508.3	127.6	36.2	9.3	74.0	37.0	80.1	40.1
13.0	20.0	0.8	2499.6	127.2	36.2	9.3	66.8	33.4	72.4	36.2
14.0	20.0	0.9	2490.9	126.7	36.2	9.3	60.4	30.2	65.4	32.7
15.0	20.0	1.0	2482.2	126.3	36.2	9.3	54.6	27.3	59.1	29.6
16.0	20.0	1.1	2473.7	125.8	36.2	9.3	49.3	24.7	53.4	26.7
17.0	20.0	1.2	2465.1	125.4	36.2	9.3	44.5	22.3	48.2	24.1
18.0	20.0	1.3	2456.7	125.0	36.2	9.3	40.2	20.1	43.6	21.8
19.0	20.0	1.5	2448.3	124.5	36.2	9.3	40.0	20.0	40.0	20.0
20.0	20.0	1.6	2439.9	124.1	36.2	9.3	40.0	20.0	40.0	20.0
21.0	20.0	1.8	2431.6	123.7	36.2	9.3	40.0	20.0	40.0	20.0
22.0	20.0	2.0	2423.4	123.3	36.2	9.3	40.0	20.0	40.0	20.0
23.0	20.0	2.2	2415.2	122.9	36.2	9.3	40.0	20.0	40.0	20.0
24.0	20.0	2.4	2407.1	122.4	36.2	9.3	40.0	20.0	40.0	20.0
25.0	20.0	2.7	2399.0	122.0	36.2	9.3	40.0	20.0	40.0	20.0

Appendix H.2 Prediction of volume of media and EBRT based on two conditions (production of nitrite and nitrate under experiment condition and maximum nitrification rate) with the effect of temperature for airflow (qs)2000 L/s, temperature (t1)10 to 20°C, ammonia concentrations (c1) 10 ppmv

t1	c1	a	cgit	ect	y3	y4	V2	EBRT2	V3	EBRT3
10.0	10.0	0.6	1263.0	71.4	17.5	6.7	85.1	42.5	49.1	24.5
11.0	10.0	0.7	1258.6	71.2	17.5	6.7	76.9	38.4	44.3	22.2
12.0	10.0	0.7	1254.2	70.9	17.5	6.7	69.5	34.7	40.1	20.0
13.0	10.0	0.8	1249.8	70.7	17.5	6.7	62.7	31.4	40.0	20.0
14.0	10.0	0.9	1245.4	70.4	17.5	6.7	56.7	28.3	40.0	20.0
15.0	10.0	1.0	1241.1	70.2	17.5	6.7	51.2	25.6	40.0	20.0
16.0	10.0	1.1	1236.8	70.0	17.5	6.7	46.3	23.1	40.0	20.0
17.0	10.0	1.2	1232.6	69.7	17.5	6.7	41.8	20.9	40.0	20.0
18.0	10.0	1.3	1228.3	69.5	17.5	6.7	40.0	20.0	40.0	20.0
19.0	10.0	1.5	1224.1	69.2	17.5	6.7	40.0	20.0	40.0	20.0
20.0	10.0	1.6	1220.0	69.0	17.5	6.7	40.0	20.0	40.0	20.0

Appendix H.3 Prediction of volume of media and EBRT based on two conditions (production of nitrite and nitrate under experiment condition and maximum nitrification rate) with the effect of temperature for airflow (qs)2000 L/s, temperature (t1) 15°C, ammonia concentrations (c1) 2 to 20 ppmv

t1	c1	a	cgit	ect	y3	y4	V2	EBRT2	V3	EBRT3
15.0	2.0	1.0	248.2	15.3	4.4	4.7	40.0	20.0	40.0	20.0
15.0	3.0	1.0	372.3	22.7	6.0	4.9	40.0	20.0	40.0	20.0
15.0	4.0	1.0	496.4	29.9	7.5	5.2	40.0	20.0	40.0	20.0
15.0	5.0	1.0	620.6	37.0	9.1	5.4	42.6	21.3	40.0	20.0
15.0	6.0	1.0	744.7	43.9	10.8	5.7	45.3	22.6	40.0	20.0
15.0	7.0	1.0	868.8	50.7	12.4	6.0	47.3	23.7	40.0	20.0
15.0	8.0	1.0	992.9	57.4	14.1	6.2	48.9	24.5	40.0	20.0
15.0	9.0	1.0	1117.0	63.9	15.8	6.5	50.2	25.1	40.0	20.0
15.0	10.0	1.0	1241.1	70.2	17.5	6.7	51.2	25.6	40.0	20.0
15.0	11.0	1.0	1365.2	76.4	19.3	7.0	52.0	26.0	40.0	20.0
15.0	12.0	1.0	1489.3	82.5	21.1	7.2	52.7	26.3	40.0	20.0
15.0	13.0	1.0	1613.5	88.4	22.9	7.5	53.2	26.6	40.0	20.0
15.0	14.0	1.0	1737.6	94.2	24.7	7.7	53.6	26.8	41.4	20.7
15.0	15.0	1.0	1861.7	99.9	26.5	8.0	53.9	27.0	44.3	22.2
15.0	16.0	1.0	1985.8	105.4	28.4	8.2	54.1	27.1	47.3	23.6
15.0	17.0	1.0	2109.9	110.8	30.3	8.5	54.3	27.2	50.2	25.1
15.0	18.0	1.0	2234.0	116.1	32.3	8.7	54.4	27.2	53.2	26.6
15.0	19.0	1.0	2358.1	121.2	34.2	9.0	54.5	27.3	56.1	28.1
15.0	20.0	1.0	2482.2	126.3	36.2	9.3	54.6	27.3	59.1	29.6
15.0	20.0	1.0	2482.2	126.3	36.2	9.3	54.6	27.3	59.1	29.6

Appendix H.4 Prediction of volume of media and EBRT based on two conditions (production of nitrite and nitrate under experiment condition and maximum nitrification rate) with the effect of temperature for airflow (qs)2000 L/s, temperature (t1)17°C, ammonia concentrations (c1) 2 to 20 ppmv

t1	c1	a	cgit	ect	y3	y4	V2	EBRT2	V3	EBRT3
17.0	2.0	1.2	246.5	15.2	4.4	4.7	40.0	20.0	40.0	20.0
17.0	3.0	1.2	369.8	22.5	6.0	4.9	40.0	20.0	40.0	20.0
17.0	4.0	1.2	493.0	29.7	7.5	5.2	40.0	20.0	40.0	20.0
17.0	5.0	1.2	616.3	36.8	9.1	5.4	40.0	20.0	40.0	20.0
17.0	6.0	1.2	739.5	43.6	10.8	5.7	40.0	20.0	40.0	20.0
17.0	7.0	1.2	862.8	50.4	12.4	6.0	40.0	20.0	40.0	20.0
17.0	8.0	1.2	986.1	57.0	14.1	6.2	40.0	20.0	40.0	20.0
17.0	9.0	1.2	1109.3	63.4	15.8	6.5	41.0	20.5	40.0	20.0
17.0	10.0	1.2	1232.6	69.7	17.5	6.7	41.8	20.9	40.0	20.0
17.0	11.0	1.2	1355.8	75.9	19.3	7.0	42.5	21.2	40.0	20.0
17.0	12.0	1.2	1479.1	81.9	21.1	7.2	43.0	21.5	40.0	20.0
17.0	13.0	1.2	1602.3	87.8	22.9	7.5	43.4	21.7	40.0	20.0
17.0	14.0	1.2	1725.6	93.6	24.7	7.7	43.8	21.9	40.0	20.0
17.0	15.0	1.2	1848.9	99.2	26.5	8.0	44.0	22.0	40.0	20.0
17.0	16.0	1.2	1972.1	104.7	28.4	8.2	44.2	22.1	40.0	20.0
17.0	17.0	1.2	2095.4	110.0	30.3	8.5	44.3	22.2	41.0	20.5
17.0	18.0	1.2	2218.6	115.3	32.3	8.7	44.4	22.2	43.4	21.7
17.0	19.0	1.2	2341.9	120.4	34.2	9.0	44.5	22.3	45.8	22.9
17.0	20.0	1.2	2465.1	125.4	36.2	9.3	44.5	22.3	48.2	24.1
17.0	20.0	1.2	2465.1	125.4	36.2	9.3	44.5	22.3	48.2	24.1

Appendix I: Measurement of the Moisture Content

Moisture of the compost material at the end of Trial 1								
Locations	Compost+ Container.(gr.)	Container (gr.)	Wet compost (gr.)	Dry compost+ container (gr.)	Dry compost (gr.)	Water (gr.)	Moisture % Wb	Ave. % wb
Top	432.2	16.7	415.5	146.1	129.4	286.1	68.9	
Middle	479.7	16.9	462.8	166.1	149.2	313.6	67.8	
Bottom	550.7	16.8	533.9	182.4	165.6	368.3	69.0	
Average								68.5
Top	442	16.2	425.8	158.6	142.4	283.4	66.6	
Middle	496.4	15.7	480.7	163.4	147.7	333	69.3	
Bottom	511.1	16.1	495	173.8	157.7	337.3	68.1	
Average								68.0
Top	530.2	16.1	514.1	176.8	160.7	353.4	68.7	
Middle	533.8	15.9	517.9	183.9	168	349.9	67.6	
Bottom	502.6	15.8	486.8	167.6	151.8	335	68.8	
Average								68.4
Top	561.8	15.7	546.1	180.9	165.2	380.9	69.7	
Middle	536.7	15.7	521	167.7	152	369	70.8	
Bottom	528.8	16.2	512.6	187.2	171	341.6	66.6	
Average								69.1
							Total Ave.	68.5
Moisture of the compost material at the end of Trial 2:								
Top	376.2	16.8	359.4	132.5	115.7	243.7	67.8	
Middle	388.4	16.8	371.6	127.5	110.7	260.9	70.2	
Bottom	367.5	16.8	350.7	115.6	98.8	251.9	71.8	
Average								69.9
Top	360	16.1	343.9	122	105.9	238	69.2	
Middle	370	15.8	354.2	125.5	109.7	244.5	69.0	
Bottom	385.5	16.2	369.3	124.3	108.1	261.2	70.7	
Average								69.7
Top	388.6	16.1	372.5	143.9	127.8	244.7	65.7	
Middle	396.4	15.8	380.6	133.6	117.8	262.8	69.0	
Bottom	410.8	15.9	394.9	130	114.1	280.8	71.1	
Average								68.6
Top	355.7	16.1	339.6	122.4	106.3	233.3	68.7	
Middle	330.3	15.7	314.6	112.3	96.6	218	69.3	
Bottom	346.8	16.2	330.6	112.4	96.2	234.4	70.9	
Average								69.6
							Total Ave.	69.5

Appendix J: Measurement of the Void Space of the Wet Media

The procedure of measurement of the void space and real EBRT is discussed in Chapter 2.

Real E.B.R.T. of compost material at the end of trial 1					
locations	Compost + cont. (kg.)	Container (kg.)	Compost (kg.)	Volume (L)	Void Volume (L)
B.F. 1	14	1.02	12.98	20	8.8
	14	1.02	12.98	20	8.9
B.F. 2	14.98	1.02	13.96	20	8
	14.38	1.02	13.36	20	8.6
B.F. 3	13.56	1.02	12.54	20	9.1
	14.46	1.02	13.44	20	8.1
B.F. 4	14.88	1.02	13.86	20	7.94
	13.74	1.02	12.72	20	8.8
Ave.			13.23	20	8.53
Void space = 43%					0.66
Ave. Density of compost material with 69% moisture = 0.66 kg/L					